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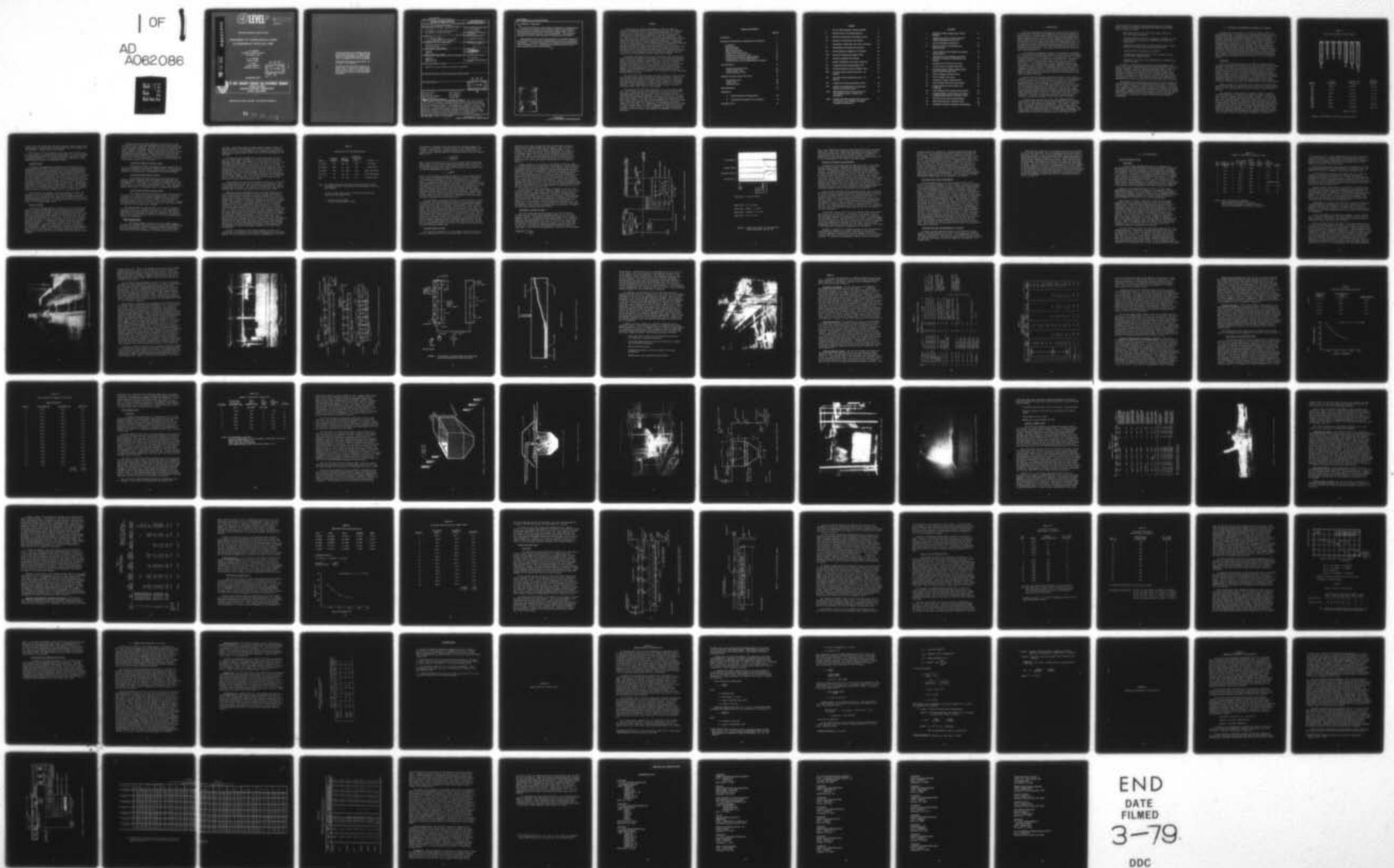

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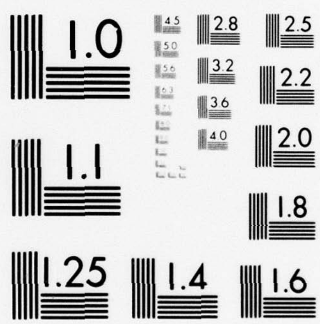

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DEVELOPMENT OF A WATER DELUGE SYSTEM TO EXTINGUISH M-1 PROPELLANT FIRES

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In support of the U.S. Army Modernization Program, and the modernized 105-mm, M-67, bag loading and assembly operations, an effective water deluge system was designed and tested to extinguish a fire should it occur in either the bulk M-1 receiving hoppers, or the bagged M-1 accumulator conveyors. The feasibility of using a water deluge was first demonstrated, then a deluge system was designed which carefully considered the in-plant conditions when selecting an appropriate fast-response detector, a rapid-acting water valve, and the water pressure and water availability at the Indiana AAP.

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20. ABSTRACT (Continued)

To evaluate the ability of a water deluge to extinguish M-1 propellant fires, full scale tests were conducted under the most stringent in-plant conditions. Plant construction and layout were simulated to evaluate effects of rising temperatures and pressures prior to fire extinguishment. Time response of the detectors and time to water application were monitored and recorded.

Detailed designs of the unique deluge systems for both hopper and accumulator applications are given and are demonstrated to meet the two predominent requirements: 1) ability to extinguish the fire without severe building damage and fire propagation, and 2) a deluge system operating within the limits of water pressure and water volume available.

SUMMARY

In support of the Indiana Army Ammunition Plant and under the direction of ARRADCOM, Manufacturing Technology Division, SwRI conducted a series of full-scale tests to evaluate the effectiveness of a water deluge system in combating M-1 propellant fires and the prevention of a propellant fire from transcending into a high order detonation. The U.S. Army is currently involved in a Production Base Modernization Program under which many new explosive and propellant production facilities are being built and others are being renovated and modernized. Significant attention is being given to both increased safety and production efficiencies for the in-process operations. For each new facility such as the modernized 105-mm, M-67, bag loading and assembly plant at the Indiana AAP, specific areas of the operation are singled out as being particularly hazardous and full-scale tests had to be designed and conducted to evaluate the extent of these hazards and methods by which the personnel exposure and potential facility damage could be significantly reduced.

The program described in this report evaluated various fire detection sensors which are available and the design of a water deluge system which could contain and extinguish a propellant fire. Critical constraints were placed on the test series to conduct full-scale tests and to simulate building restrictions related to the proximity of roof and walls and the location of the detectors in construction of the water deluge system. Design of the water system had to consider the water pressure and water adequacy at the Indiana AAP and ignition of the propellant fires was always assumed to occur at the bottom of the propellant bed, thus simulating the most severe fire case.

Full-scale fire tests were conducted under conditions simulating three process operations in the propellant bag loading operations. These locations were receiving hoppers, containing up to 450 kg of M-1 propellant, the propellant bag conveyor line, and the large accumulators containing more than 500 kg of propellant. Because of the quantities of propellant involved in these operations, they were assigned a rating of Class 1.1 explosives rather than a Class 1.3 fire hazard.

The results of the test series described in the report demonstrated that a water deluge system could be designed to operate within the available water pressure and that the system could control and eventually extinguish large hopper and accumulator fires. An evaluation of the available fire detectors demonstrated that a UV detector was the most reliable sensor and, because of its rapid action in sensing and triggering of the water deluge system, a fire could be extinguished prior to its transcending into a high order detonation and prior to its causing any significant damage to the facility. As a consequence of the demonstrated effectiveness of a water deluge system, the report recommends that these operations be assigned a rating of Class 1.3 thus eliminating the expensive additional construction that would have been necessary to accommodate an explosive operation.

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I. INTRODUCTION

Propellant and explosive technology has strived, over the years, to provide the most efficient safety methods for the in-process operations. This attention to increased safety and efficiency has been addressed in detail recently as part of the U.S. Army's Production Base Modernization Program under which many new explosive and propellant production facilities are being built and others are being renovated and modernized. In the interests of safety, many problem areas or techniques were identified as being severe hazard conditions and investigations were initiated to find means to reduce these hazards while maintaining minimal plant costs, and maximum plant efficiency. This report will describe the results of three such investigations.

At the Indiana Army Ammunition Plant, two problems were encountered when a conventional overhead water sprinkler system failed to extinguish M-1 propellant fires that originated in a receiving hopper and in a bagged propellant accumulator. The inability of the sprinklers to provide an adequate quantity of water at the source of the fire in a time frame necessary to control the magnitude of the fire's intensity caused this failure. To address these problems, ARRADCOM, Manufacturing Technology Division, together with Southwest Research Institute (SwRI) surveyed the possible options of remodeling the existing water system or designing a totally new system. Both options had to be considered in light of construction costs, delays in production schedules, system complexities, water adequacy of the plant facility and an expeditious time frame to complete the study.

The first and most important question was whether a water system, regardless of cost or water application rate, could control and extinguish a large propellant fire in time to prevent transition to a detonation and resultant major property damage. At the Indiana AAP, the new Modernized 105-mm, M-67, Bag Loading and Assembly Plant required up to 453.6 kg receiving hoppers and up to 544.3 kg in each of seven accumulators to maintain production rates necessary for the facility. These two large holding vessels would also violate an Army Materiel Command Safety Regulation which states that a maximum propellant height in any single container must not exceed 45.7 cm in order to satisfy a Class 1.3 operation. As a Class 1.1 explosion operation, production would be curtailed or expensive additional construction would be necessary.

To answer this vital question, SwRI, under ARRADCOM guidance, contracted to design and test a water deluge system for use in fighting fires in full-scale hoppers and accumulators. Two series of tests were made. The initial test series verified that a water deluge could be used to extinguish large propellant fires, and that by controlling the rate of burn, the deflagration did not transcend into a detonation. The second series of tests was carried out in a more sophisticated manner to study the most critical fire conditions, and a water deluge system

compatible with the in-plant water supply and water line pressures. Thus, critical, but realistic restraints were placed on the second series of tests as follows:

- Full scale tests of up to 453.6 kg in hoppers and up to 544.3 kg in each accumulator

- In-plant building restrictions, relating to proximity of roof, walls, location of detectors, construction of hoppers and accumulators

- Commercially available fire detectors would be used to sense the fire at the top surface of the propellant bed

- A maximum static water pressure of 448 kPa

- A maximum water application rate of 611.13 $L/M/m^2$ to meet in-plant water adequacy limits

- Ignition at the bottom of the propellant bed to simulate most severe fire case.

Discussion of experiments, the details of the experiments, the design of the water deluge system, and the techniques used to record the data are discussed. The test evaluation shows the results of the test firings. Several significant conclusions are drawn from the test results with regard to the design and functioning of a deluge system and these conclusions are noted on page 63. By application of these results to the design and construction of explosive and propellant manufacturing facilities, it is believed that safety can be significantly improved and at a lower cost than with many techniques used in the past.

Two Appendices are included with the report to give the reader more depth and appreciation of the complexities involved, first in defining the fire hazard, and second, in the selection of equipment to attack the fire. Appendix A attempts to relate, by analytical methods, the quantity of propellant burned to the would-be pressure rise in the actual in-plant environment. Appendix B describes the results of almost 300 test firings made to compare the sensitivity and response times of three detectors to a variety of fire sources as viewed through several atmospheric contaminants.

II. DISCUSSION OF EXPERIMENTS--EQUIPMENT AND TECHNIQUES

The purpose of this program is to obtain the design criteria for water deluge systems to be installed in a 105-mm, M-67 propellant charge loading facility and to demonstrate that these systems will provide personnel, equipment and facility protection. The testing program to be described herein was conducted to determine the required operating characteristics and flow rates of a water deluge system, to provide and to demonstrate the adequacy of the system design, and to eliminate or minimize damage resulting from any incident. The testing program was designed to simulate three areas of the modernized 105-mm, M-67 bag loading assembly and packing (LAP) operations at the Indiana Army Ammunition Plant. These three areas had been identified by a safety analysis study as being particularly hazardous areas in which fires have in the past occurred. This section of the report will describe the equipment and experimental techniques used in the conduct of the test evaluation program.

Propellant

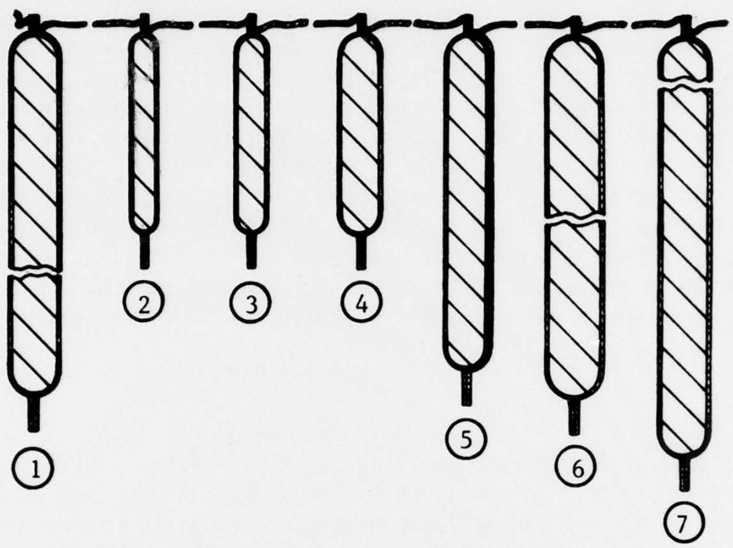
All of the tests were conducted using both the single perforated and the multi-perforated M-1 propellant as used in the 105-mm, M-67 charge assembly. The grains of M-1 propellant are manufactured in two forms: the single perforated propellant grain measures 0.114 cm in diameter by 0.508 cm long, and the multi-perforated propellant measures 0.305 cm diameter by 0.813 cm long. The single perforated grain has a single 0.033 cm diameter hole in the center, and the multi-perforated propellant has seven 0.064 cm diameter perforations. The bulk densities are approximately 849 kg/m^3 for multi-perforated and 625 kg/m^3 for the single perforated propellant. M-1 propellant contains 84.2% nitrocellulose (13.15% N), 9.9% dinitrotoluene, 4.9% dibutylthalate, and 1% diphenylamine.

These two forms of M-1 propellant are received at the Indiana Army Ammunition Plant and are unloaded from trucks into large receiving hoppers. Hence, for the testing program involving the hoppers, loose propellant was used.

The propellant is then transferred through a series of steps by which the propellant is loaded into increment bag charges, seven bags constituting the complete 105-mm, M-67 charge. Table I shows that bag Nos. 1 and 2 contain the single perforated, while bags 3-7 contain the multi-perforated propellant. Each bag increment is loaded at a separate station, and the bags are fed individually, one behind the other, along a conveyor which eventually feeds into a large accumulator (holding tray). For the SwRI tests of the Line Burn deluge and the Accumulator deluge, bagged M-1 propellant was used. To further simulate the in-plant conditions, the bags were aligned end-to-end in a single layer for the Line Burn tests, whereas in the Accumulator the bags were randomly stacked up to 41 cm deep. Seven of these large accumulators are located in a

TABLE I

105 mm, M67 Propellant Charge Assembly



Bag No.	S Or M Propellant	Propellant Wgt. ozs/g	Approx. Bag Length in./m
1	Single	8.28/235	11½/.292
2	Single	1.37/39	4/.102
3	Multi	2.26/64	4/.102
4	Multi	3.61/102	4/.102
*5	Multi	5.03/143	6/.152
6	Multi	8.43/239	8½/.216
7	Multi	13.0/369	11½/.292
	TOTAL	42.78/1214	

*Bag No. 5 has 0.008 cm Lead Foil Covering One Side

single room at the Indiana AAP, and each accumulator simultaneously feeds a single bag to a sewing station at which point the seven increments are sewn together to make up the full M-67 charge.

This review of the LAP operation briefly identifies the three areas that were judged to be potential fire hazard areas: the receiving hopper, the individual bags being fed into the accumulator (line burn), and the accumulators themselves. In succeeding sections of this report, these three hazardous areas will be identified further.

Ignition Source

To evaluate the magnitude of the potential fires in each of the three hazardous locations, it was desired to cause an instantaneous and vigorous fire, yet at the same time not to cause an overkill situation. It was found in preliminary experiments that the single perforated M-1 propellant would ignite easily using only an M-100 Atlas electric match. The multi-perforated M-1 propellant was, however, more difficult to ignite, and it was found to be necessary to "boost" the electric match ignition in order to ensure a vigorous ignition. Several different booster charges were used in the early testing, ranging from 20 g of loose M-1 single perforated propellant to as much as 58 g of black powder. Through these experiments, it was found that a booster charge of 2g of black powder would serve as an adequate booster charge and not overkill the situation; hence, for all of the multi-perforated confirmatory shots, the ignition system consisted of an electric match plus 2g of black powder.

For all of the test firings, ignition was caused to occur at the bottom of either the accumulator or the receiving hopper. Since the accumulator tests and the line burn tests used the bagged propellant, the ignition source was placed inside a single bag, and that bag, of course, was surrounded by other bags. In all tests, the electric match was fired using a 24 v DC battery energy source.

Detector Systems

In order for a deluge system to extinguish a fire on a processing line in an explosives handling facility, the system must have a sensor which will detect the fire and a control system which will activate a water valve within milliseconds of the fire appearing in the view of the detector. The detector cannot normally be located physically near the most probable point where fire could occur. Therefore, the sensor must be capable of detecting a fire at a distance of up to 6.10 m. Usually there is some solvent, including water, present during the explosives handling processes, or, dust may be created, or the fire may be obscured by smoke. The sensor must be able to detect a fire through such atmospheres. Finally, the sensor must not give false alarms, as for example when sunlight or incandescent or fluorescent lights suddenly appear in the view of the sensor. Such false alarms would result in stoppage of the processing line and in undue loss of the explosive being processed.

The three detector systems evaluated are ones which have been selected for use in explosives handling facilities or were selected as a result of earlier programs. All three of the detector systems react to electromagnetic radiations emitted by the fire, or in short the flames, visible or invisible. These radiation sensitive detectors have the capability of sensing fire remotely and quickly, which the more commonly-encountered household or industrial sensor systems do not. These detector systems either use, or can use, a relay to operate the water valve. Each of these detector systems uses a different band of radiation wave lengths in its operation.

- Ultraviolet Sensitive Detector System

The ultraviolet sensitive detector system evaluated was the Det Tronics DE-R7300A controller and C7037B detector. This detector is sensitive to radiation in the 1850 to 2450Å (0.18-0.24μ) range, and is insensitive to sunlight and to incandescent and fluorescent lights.

- Infrared Sensitive Detector System

The infrared sensitive detector system evaluated was the American District Telegraph (ADT) 5925 SIGMAC Ultra-high-speed fire detection system. This detector is sensitive to radiation in the 7000 to 28,000Å (0.7 - 2.8μ) range, and is sensitive to sunlight and incandescent light, but insensitive to fluorescent light. This system must be masked from sunlight or incandescent light to preclude false alarms.

- Visible Light Sensitive Detector System

The visible light sensitive detector system evaluated was the Pyrotector, Inc., Model Optical Fire Detection System. This detector is sensitive to radiation in the 6000 to 8500Å (0.6-0.85μ) range for detection of fire, and in the 4000 to 5200Å (0.4-0.52μ) range for precluding false alarms due to sunlight. This system therefore uses near infrared radiation to sense a fire, but uses a blue light bias to reduce the instance of false alarm due to sunlight.

The response times of these detectors to the Hopper, Accumulator, and Line Burn fires are reported in Section III. For a comparative evaluation of the three detectors, Appendix B describes the results of almost 300 test firings made to evaluate the sensitivity and response times of each detector viewing a variety of fire sources through several atmospheric contaminants.

Water Deluge System

The primary design criterion of any water deluge system is to provide the necessary liters per minute per square meter (LPM/m^2) area coverage to be effective in restraining and eventually extinguishing a fire. The system must, however, be compatible with the static line pressures and total water adequacy of the plant in which it is to be

installed. These restrictions of water pressure and water adequacy at the Indiana AAP were the governing factors for the design of the water deluge to be used in the test program. For purposes of explanation, the complete water deluge system used by SwRI in the testing program will be described.

The SwRI field test program used a 15,140 liter tank as a water supply, and this supply was pumped to the water deluge system using a Hale pump, Model 50FB. This pump had 12.7 cm suction line and a 10.2 cm discharge line pumping water at 1514 liters per minute at a distance of 137.2 meters from the pump to the test pad. The output of the pump could be varied to control the effective static line pressure at the test site and to control the liters per minute discharge through the water deluge nozzles. Prior to testing, all of the water lines from the pump through the output nozzles were preprimed, and flow of the water was controlled by the use of an in-line Primac high-speed valve manufactured by the Grinell Company. This valve uses two explosive primers (Hercules MK131) to shear a holding pin, at which time the line water pressure forces open a valve, thus releasing the water.

In the Indiana Line Burn Tests described in Section III, a "Pilotex" Water Deluge System was used and its performance was compared to that of the Primac Valve system. The Pilotex system requires a more complex plumbing network, however, once installed, it worked quite well and the response time to water-on was quicker than for the Primac system.

Downstream from the high-speed valve to the water deluge nozzles, the system was designed following the hydraulic design principles set forth in National Fire Protection Association Standards Nos. 13 and 15. Realistically, however, the SwRI test system had to be flexible so that changes could be instituted rapidly to evaluate the good and bad features of the design parameters. The primary governing factor for the system, however, was the static line pressure, which in all cases was held to a maximum of the 448 kPa available at the Indiana AAP. For economic reasons, the deluge system was also limited by the desire to purchase only a few nozzles and have them serve over a wide latitude of test conditions. In order to provide the latitudes of water coverage dictated by the deluge design and by the anticipated coverage required to extinguish the fires, SwRI purchased four types of nozzles from the Grinell Company and fabricated a fifth nozzle design in its own machine shop. The specifications of these five nozzles are given in Table II and typical values of the water discharge in liters per minute are shown. The specific nozzles used for each of the tests to be carried out will be described in Section II of this report, and Figures 6, 12 and 16 clearly indicate which nozzles were used, the physical placement of those nozzles, and, all important, the LPM per square meter coverage of each water deluge configuration.

In order to satisfy the critical water adequacy problem at the Indiana AAP, it was desired in all of the test firings to use the minimum quantity of water required for the effective extinguishment of the fire.

TABLE II

Nozzles Used For The Deluge Systems

Type	Discharge Angle	Nominal LPM Range	Discharge Coefficient (K)	Use
S-1-50-12	50°	38 - 76	1.95	Area Spray
S-1-100-16	100°	57 - 114	2.52	Area Spray
R-1-90-29	90°	95 - 189	4.61	Heavy Area Spray
R-1-45-41	45°	132 - 227	6.30	Heavy Area Spray
SwRI	10°	76 - 227	~5.0	Cut-Off Deluge

Note: All nozzles were fitted with blow-off plastic caps to allow prepriming of lines. Caps blow-off at approximately 137.9 kPa line pressure.

"Pilotex" system used for part of the Line Burn Tests (see Section III) not listed above.

* 1 gallon per minute (GPM)
= 3.785 liters per minute (LPM)

Consequently, the design of the water deluge was governed primarily by the static line pressure on the one side and by the minimum LPM/m^2 area coverage at the other end. Hydraulic design criteria established the validity of the following empirical relationship based on the now outmoded English units.

$$P = \frac{4.52\ Q^{1.85}}{C^{1.85} D^{4.89}}$$

where P is the friction loss in psi, Q is the volume flowing through the pipe in GPM, C is the friction coefficient (nominally 120), and D is the inside diameter of the pipe. This relationship was used to calculate the pressure existing at each outlet nozzle, and this value could be used in the next relationship as follows:

$$Q = K\sqrt{P}$$

where Q = the discharge in gallons per minute, K = the discharge coefficient, and P is the pressure existent behind each nozzle. The value of K, the discharge coefficient for each of the nozzles used, is shown in Table II. The water flowed out each of the nozzles in a cone-shaped pattern dependent upon the design of the nozzle. The approximate included spray angle for each of the nozzles used is also given in Table II. Using a projection of the nozzle cone angle and knowing the height in feet above the surface to be protected, the spray pattern and gallons per minute rate of application on the fire can be estimated. The reader is cautioned, however, that none of the nozzles tested had a uniform spray pattern. Also, the pattern changed with changing line pressures. Hence, the application rate over an area can be calculated, but not the application on a particular spot within that area.

Two experimental techniques were used to verify the hydraulic design calculations. The first technique consisted of placing pressure gauges at various points along the main water line and monitoring the residual pressure while the water was flowing. Simultaneously, a pitot tube was placed under each nozzle to determine the rate of water flow from that nozzle. The second experimental technique consisted of using simple catch buckets which were placed on the conveyor trays at the same distance from the nozzle as would be the propellant in the experimental tests. These catch buckets had a known presented area, and rate of water flow into the buckets as a function of time could be monitored. It is significant to note that each of these three techniques yielded approximately the same value of LPM per square meter within a maximum variation of less than 20 percent. The reported values of LPM per square meter given for the line burn, accumulator and hopper tests reflect an average value obtained from the three techniques noted above.

Sequence Timing of Events

To validate the response of the fire sensor to detect the fire, to actuate a high-speed valve, and to release water to the fire, the time

response of each event for each test shot was monitored. The event timing network is shown schematically in Figure 1, and each event is monitored as a function of time from the ignition pulse. In the schematic, the ignition pulse is shown to ignite the fire, start the oscilloscope traces, and activate a flash bulb which is monitored by a high-speed camera. The four-channel oscilloscope electronically monitors the time from the ignition pulse to the activation of the UV detector, to the firing of the Primac detonator, to the shorting of a water-on switch, and in some cases to the activation of a backup IR detector.

Special attention is called here to the points at which the times to be cited in Section III of this report were measured. Recent experience in reviewing reports and instrumentation specifications reveals that each investigator had his own experimental setup, and each measured the time response of the various instruments at possibly different points along the event timing network. To be very specific and avoid misunderstanding, for the tests described herein, the response time of the UV detector was monitored from the ignition pulse (A_I) to the activation of the sensor (D_o)*. The second oscilloscope trace measured the time between ignition and the output pulse of the detector relay (G_o). This is the pulse that triggers the Primac water valve. The third oscilloscope trace measures the time from the ignition pulse to the activation of a simple mechanical switch which was placed under one of the water nozzles and was shorted as soon as the water came out of the nozzle (Ko).

A typical oscilloscope trace showing the timing of the four events is shown in Figure 2. This record, taken from Hopper Test No. 16, clearly shows the form of the scope traces, and the relative response time of each event after sweep-start (ignition). Obviously, the longest delay, ignition to UV detection (A_I-D_o), is caused by the delay for the propellant to burn from bottom ignition to top detection, a distance of 68.6 cm for this 181.4 kg test. The time from UV detection to functioning of the Primac (D_o - G_o) was 30 msec, and from Primac Valve to water-on (G_o - K_o) was 180 msec. The UV detector can also be seen in the scope trace to be approximately 50 msec faster in response than the IR detector. Throughout the tests these response times were typical.

Photographic Coverage of Tests

Each test firing was recorded using both a real-time camera at 24 frames per second (fps) and a high-speed camera set to run at 168 frames per second. The high-speed camera was equipped with a time-mark generator light to calibrate the actual framing speed. This calibration showed the true framing speed to be 146 fps, not 168 fps. Hence, when converting the Hycam times to real-time, a divisor of 6.09 rather than 7.0 was used. The real-time camera was placed to view the event along the axis of the accumulator, and the high-speed camera was placed at right angles to view the event perpendicular to the axis of the accumulator

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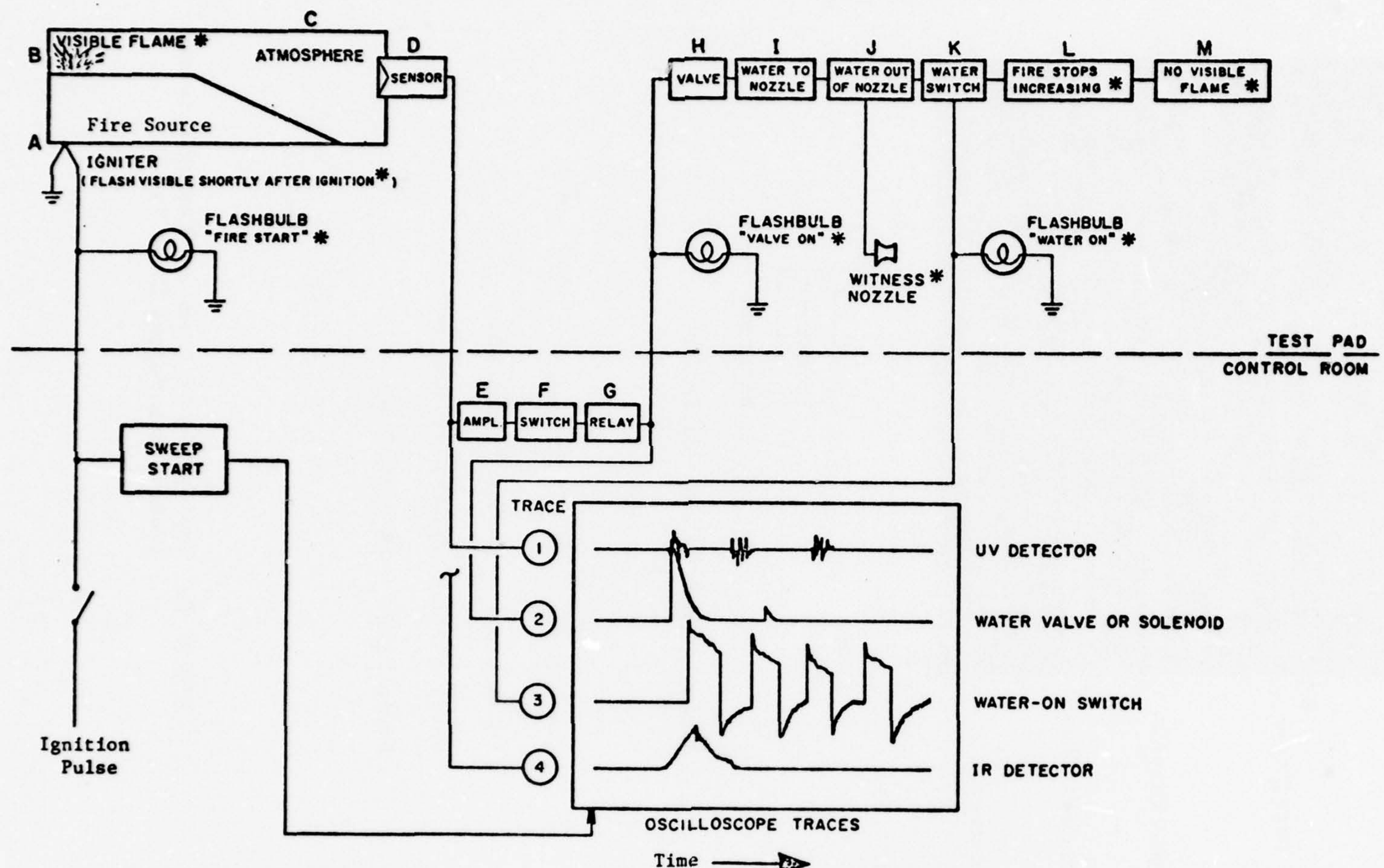
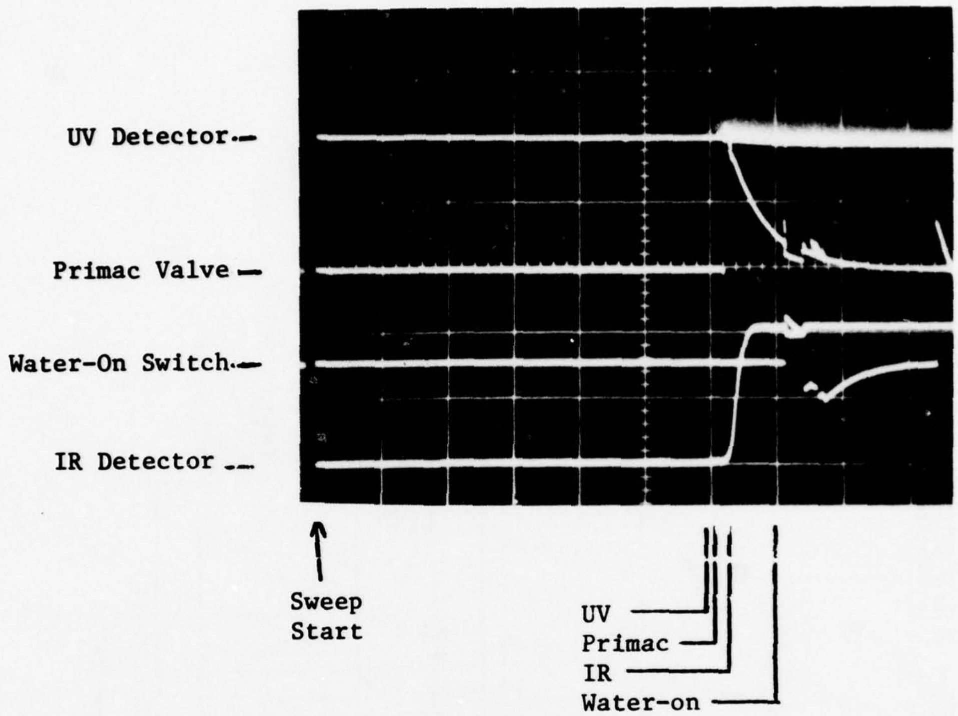
* Subscript I = input
o = output



* Seen in motion pictures.

FIGURE 1. Schematic Of Water Deluge Event-Timing Network



Sweep Rate = 0.2 sec/division

Sweep Start - UV = 1.22 sec

Sweep Start - Primac = 1.25 sec

Sweep Start - Water-on = 1.43 sec

Sweep Start - IR = 1.27 sec

FIGURE 2. Typical Scope Trace of Timing Network (Taken From Hopper Test No. 16)

tray. The flashbulbs were placed in the field of view of the high-speed camera only. Both of the cameras provided excellent coverage of the test shots and were able to give clear indication of the appearance of visible flame in the test bed, the release of water to the fire as measured by a witness nozzle placed at the end of the deluge system, and of the extinguishment of the flame by the water deluge.

Pressure and Temperature Measurements

The purpose of this program was to demonstrate that a water deluge system could be designed, installed and used effectively to combat a fire which might occur in a 105-mm, M-67 propellant charge loading facility. To demonstrate that a water system will provide personnel, equipment and facility protection, there are many criteria which could be used to measure the effectiveness of such a system. In the tests to be conducted under this program, it was first specified that ignition would occur in all cases at the bottom of the propellant bed. Since detection would always be effected on the surface of the propellant bed, some quantity of propellant will, in all cases, have been burned prior to the detection and certainly prior to the application of the water deluge. Assuming, then, that in all cases a quantity of propellant will be burned, the question arises as to how much propellant can be expended before significant damage is done to the equipment and the facility.

Since the M-67 propellant charge loading operation will, in the new modernized facility, be carriedout remotely and without human attendance, we can for the moment neglect concern over personnel protection. We are concerned, therefore, with the rise in temperature and the rise in ambient pressure in the area immediately surrounding the point at which the fire occurs. In a review of the construction of the new modernized bag loading facility, it was revealed that the receiving hoppers are contained in a large room and the hopper is vented directly out through the roof. The seven accumulators are also contained in a very large room, and this room is provided with blowout panels on the roof to alleviate any rise in pressure.

For economic reasons, all of the tests conducted under this program were carried out in the open air, although in the accumulator tests a roof was placed over the test area to partially simulate the confining and reflecting surfaces in the immediate area of either a receiving hopper or an accumulator fire. Although it was not an exact simulation, attempts were made to measure both the rise in pressure and the rise in temperature in the area immediately surrounding the test fires. Data from these measurements could then be factored into the hazards analysis; the results of that analysis are described in Appendix A of this report.

Attempts to measure rise in ambient pressure in the area immediately surrounding the accumulator and hopper fires were not successful. Pressure transducers and maxi-pointer pressure gauges were placed as close as three feet to these fires, and in no case was a rise in pressure recorded. The temperature measurements, however, were more successful.

To measure the rise in temperature, Teletemp temperature patches were placed at 3.048 m intervals on two opposite sides of the hoppers and accumulators. These Teletemp patches are calibrated to discolor in 10° increments at temperatures ranging from 10°C to 260°C; hence, after the shot the maximum temperature as a function of distance away from the fire could be measured and recorded. Temperatures as high as 177°C were recorded in some of the tests and are reported in Section III. Since the tests were conducted in the open air, it was necessary to average the upwind and the downwind measurements, and these are the values reported herein. Again, although these measurements are not precise, it is believed that they do reflect the nominal temperatures that would be felt by an adjacent piece of operating equipment or by a structural wall in the bag loading plant. One can use these approximate temperatures together with the recorded time-to-extinguish to estimate the possible damage caused to the equipment or the facility.

Propellant Burn Velocity Measurements

As an additional input to the hazard analysis study, and to a definition of the effectiveness of a water deluge to control a propellant fire, it was desired to measure the rate at which the propellant burned in the receiving hopper and the accumulator environment. Burn velocity could then be translated into the quantity of propellant burned and, hence, the rate of gas evolution as a result of the fire. Unfortunately, however, the measure of propellant burn velocity was not successful in either the accumulator or the hopper. A simple technique of using twisted pair wire which would be shorted by the burning propellant and transmit a signal to a counterchronograph was used. This technique is usually simple and quite reliable. However, when a propellant bed is ignited at the bottom, the rate of gas evolution causes an "eruption" which lifts and loosens the entire propellant bed, allowing for the venting of hot gases to the successive velocity measuring stations. Consequently, the recorded measurements were often totally out of order and misleading. The high-speed motion picture records revealed this eruption phenomenon and led to the abandonment of any further efforts to measure the burn velocity. Also, because of the rapid application of water, the propellant grains were wetted down, and the rate of burn was thus retarded. The above negative comments notwithstanding, propellant burn velocities in the neighborhood of 243.8 to 610 cm/sec were recorded, and these velocities do appear to be in keeping with the total burn time of a given fire and with the weight of the propellant recovered following a fire. Where applicable, the propellant burn velocities are reported and discussed in Section III .

Propellant Recovery and Determination of Residue

No doubt, the most important measure of the success of the water deluge in extinguishing the fire was that of determining the weight of propellant recovered after the test shot. The reported data in Section III showed the percent of the original propellant mass which was recovered. The reported value always reflects the weight of the propellant in the "dried" state.

After each test firing, all of the propellant that was not burned in the test was recovered. Due to the gaseous eruption at the start of each test, and later to the forceful impingement of the water deluge, a significant quantity of loose propellant, and/or bagged propellant, was always ejected from the accumulator or hopper. This unburned material was gathered up immediately following the test firing, and this propellant was added to the propellant recovered from within the accumulator or hopper. The total mass of all propellant recovered was then weighed in the wet condition to allow for a determination of the water retention by the wet material. For those field test operations, the total mass of recovered propellant was then spread out on a concrete pad and allowed to dry for three to four days before reweighing in the dried condition. It was then possible to record the percent of water retention and the percent of propellant recovered from each shot, and these values are given in Section III.

III. TEST EVALUATIONS

Indiana Accumulator Tests

Discussion

At the Indiana Army Ammunition Plant, two problems were encountered when a conventional water deluge system failed to extinguish M-1 propellant fires that originated in a receiving hopper containing loose propellant and in an accumulator used to temporarily hold bagged M-1 propellant. An inability to provide a sufficient quantity of water at the source of the fire in a time frame necessary to control the magnitude of the fire's intensity was attributed to the failure. To address these problems, two options were possible: 1) the remodeling of the exisiting water deluge system, or 2) the design of a totally new water deluge system. Both systems had to be considered in light of construction costs, delay in production schedule, system complexity, water adequacies of the facility, and an expeditious time frame to complete the study.

Because of the extreme importance of each of the above items, ARRADCOM undertook the task of attempting to find workable solutions to these safety problems. To test the ability of a water deluge system to contain and to extinguish large M-1 propellant fires, ARRADCOM contracted with Southwest Research Institute for a brief exploratory program to simply determine if a large M-1 fire could be extinguished.

SwRI conducted a series of eight test firings in which bagged propellant, held in a simulated accumulator tray, was deliberately ignited, and a rudimentary water deluge system was used to attack the resulting fire. Table III briefly summarizes the results of these exploratory tests, and the first concern of these exploratory tests was to determine whether the propellant fire would transcend into a detonation and cause significant damage to the simulated facility (i.e., conveyor tray, roof over conveyor, fire detector, and water deluge nozzles). In the first test, only a 2.54 cm height of propellant was used, this being a single layer of the No. 3 bagged M-1 propellant. When a single bag was ignited, the ultraviolet detector immediately saw the fire, triggered the water deluge, and resulted in a 94% recovery of the No. 3 bags. In subsequent tests, the height of the propellant was increased to 10.2 cm, 20.3 cm, 30.5 cm, etc., and in each case a significant quantity of propellant was recovered.

For these exploratory tests, the water deluge system was not a very sophisticated one. A relatively slow operating solenoid valve was used to release the water, and the line beyond the solenoid valve was not preprimed prior to the tests. In addition, the static water pressure was, except for Test No. 7, held constant at 1034 kPa, which was too high for an actual in-plant water system. Although these exploratory tests were conducted under the most simple and rapid conditions, they did clearly indicate two important results: 1) the deflagration did not transcend into a detonation, and 2) a water deluge system did indeed quench

TABLE III
Summary of Exploratory Accumulator Tests

Shot/ Type	Height Of Propellant (cm)	Bag No.	Total Weight Of Propellant (kg)	Static Water Pressure (kPa)	SwRI Nozzles Used	Mass Recovered (kg)	% Recovery
1	2.45	3	6.09	1034	2	5.70	94
2	10.2	3	24.4	1034	2	13.4	55
3	20.3	4	59.4	1034	3	23.2	40
4	30.5	6	107.8	1034	4	76.2	70
5	40.6	6	136.5	1034	4	SOLENOID	FAILED
6	38.1	6	123.6	1034	4	60.3	48.8
7	30.5	4	111.1	448	4	45.4	41
8	30.5	7	112.5	1034	4	52.2	46

Notes: Water Lines were not preprimed.
Slow opening solenoid water valve used.
Water pressure too high for in-plant situation.
Fires were extinguished in every test, except No. 5.

an M-1 propellant fire. These exploratory tests also demonstrated that it should be possible to design a water deluge system that would be compatible with the water adequacies of the facility and a design which would not be too complex nor too costly for installation in a large modernized propellant production facility.

This report will discuss the design, test and evaluation of a water deluge system, designed within the constraints at the Indiana AAP, and aimed specifically at the bagged M-1 propellant accumulator trays.

In the accumulator room area at the Indiana AAP, up to 2267.9 kg bagged M-1 propellant are stacked 40.6 cm high in seven adjacent accumulators, some of which are up to 21.3 m long. The total propellant contained in the seven accumulators amounts to almost 15,875.7 kg. In the event of a fire, fire brands from the primary fire could be reflected from the roof into the adjacent accumulators and potentially all seven accumulators would eventually burn.

Because of these large quantities of propellant, it became imperative that fire detection should occur immediately. Unfortunately, the random stacking of bagged propellant prevents immediate detection of a bottom ignition source. Consequently, this time lag in detection permits extensive fire spread before a sensor can activate the water deluge system. As a result, only a fast-acting sensor was considered. Since ultraviolet and infrared detector systems have similar response times, both systems were evaluated for this application.

Compounding the problems in detection was the limitation imposed by the water supply at the Indiana AAP. Here, the success of any water deluge system design had to depend on a 448 kPa static water line pressure. With this water pressure limitation, a water deluge capable of penetrating the stacked, bagged propellant to the source of ignition had to be developed.

To meet this demand, two options were advanced: 1) area coverage and 2) a cut-off deluge system. The major difference between these two systems resides in the greater water pressure flow derived from the 10 degree angle nozzle used in the cut-off design.

Before reviewing in detail the design of the deluge system, let us look first at the experimental test setup. The primary accumulator used for the tests was a 4.6 m long section designed to simulate a portion of a 21.3 m long section used in the Indiana plant. This accumulator section, filled with 544.3 kg of bagged M-1 propellant, is shown in Figure 3. To simulate the in-plant condition, a witness accumulator was placed parallel to the donor accumulator at a distance of 45.7 cm and a roof was placed over the accumulator trays to act as a deflector of fire brands. For the tests, the worst case condition was considered, that is, bottom ignition in the donor accumulator. As the fire in the donor erupts and fire brands are projected out of the donor, these fire brands could be reflected off the roof of the building down onto the witness accumulator,

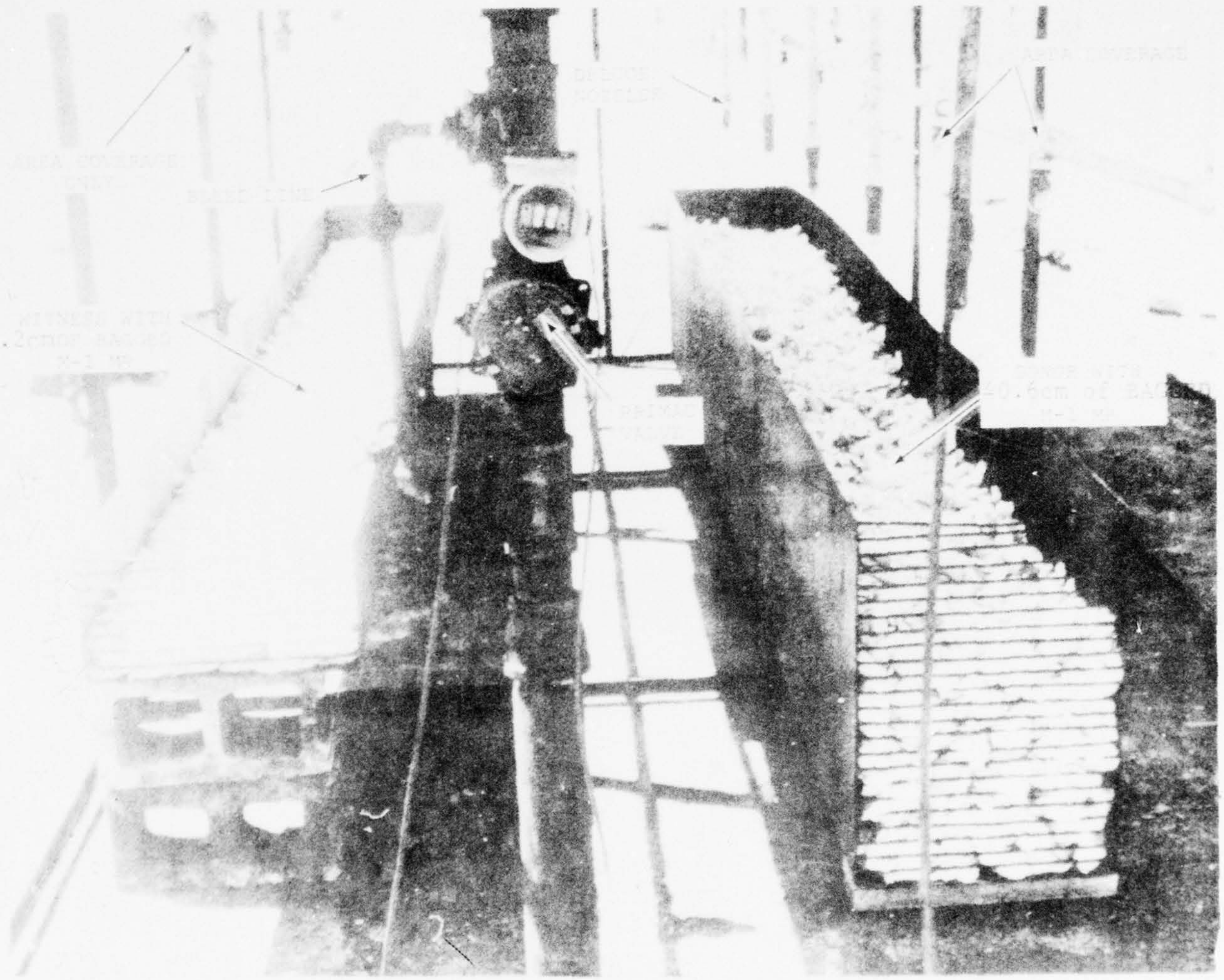


FIGURE 3. Donor And Witness Accumulators

causing surface burn. Since it was assumed that any fire in the witness accumulator would be caused by top ignition, only a 10.2 cm layer of witness bagged propellant was used in a shallow conveyor. In the foreground of the photo of Figure 3, the water line, the bleed valve and the Primac deluge valve can be seen. Figure 4 presents a side view of the experimental test setup, and both Figures 3 and 4 show the placement of the water deluge nozzles.

The water deluge systems designed to attack the fires in the donor accumulator are shown schematically in Figure 5. A series of experimental burn tests with the simple deluge system illustrated at the top of Figure 5 were performed to determine the most effective option for fire extinguishing. The area coverage deluge system resulted in a failure when the water spray could not penetrate the stacked, bagged propellant and contain the magnitude of the fire spread. A similar set of experiments were conducted (Tests 9 and 10) using a single cut-off nozzle as shown in the middle sketch of Figure 5. These two experiments using the cut-off deluge system met with success when a fire was extinguished within 2.4 m of the source of ignition.

The principle of attacking a fire in bagged M-1 propellant was thus established, however another serious problem then arose -- water adequacy at the plant. How could enough water be supplied to cut off deluge nozzles when used throughout the entire accumulator room housing over 106.7 linear meters of accumulators? To refine the system and also to consider a system which could be used in the entire accumulator room area, the water deluge system used in Tests 10 through 18 was developed and is shown at the bottom of Figure 5. This system contains two parallel water lines; one containing the deluge nozzles set at a distance of 0.91 m apart. Parallel to this line, an area coverage system is also set at 0.91 m apart. Details of this design are shown in Figure 6. The principle of operation was as follows: The detector, either UV or IR, would sense a fire in the donor accumulator and would actuate the cut-off nozzle system in that accumulator only. At the same time and through a logic circuit, the area coverage system would be activated throughout the entire accumulator room. This deluge design served two very important purposes. First, the cut-off nozzles were capable of penetrating the bagged propellant and preventing fire propagation under the surface of the propellant bed. Secondly, the area coverage not only attacked the surface fire in the donor accumulator, but also attacked any surface burning which might be occurring in the adjacent (witness) accumulator. Using this dual coverage system, it was possible to design a water deluge that could effectively fight the accumulator fire within the limits of water adequacy and the 448 kPa which was available at the Indiana AAP.

The sketch of Figure 6 shows the area coverage provided 101.9 LPM/m^2 over both the donor and the witness, while the cut-off nozzles provided a penetrating jet of water rated at 472.6 LPM/m^2. More importantly, the cut-off nozzles provided a penetrating jet of water which was capable of separating the bagged propellant and penetrating through the bottom of the accumulator bed. Figure 7 illustrates the principle of the cut-off

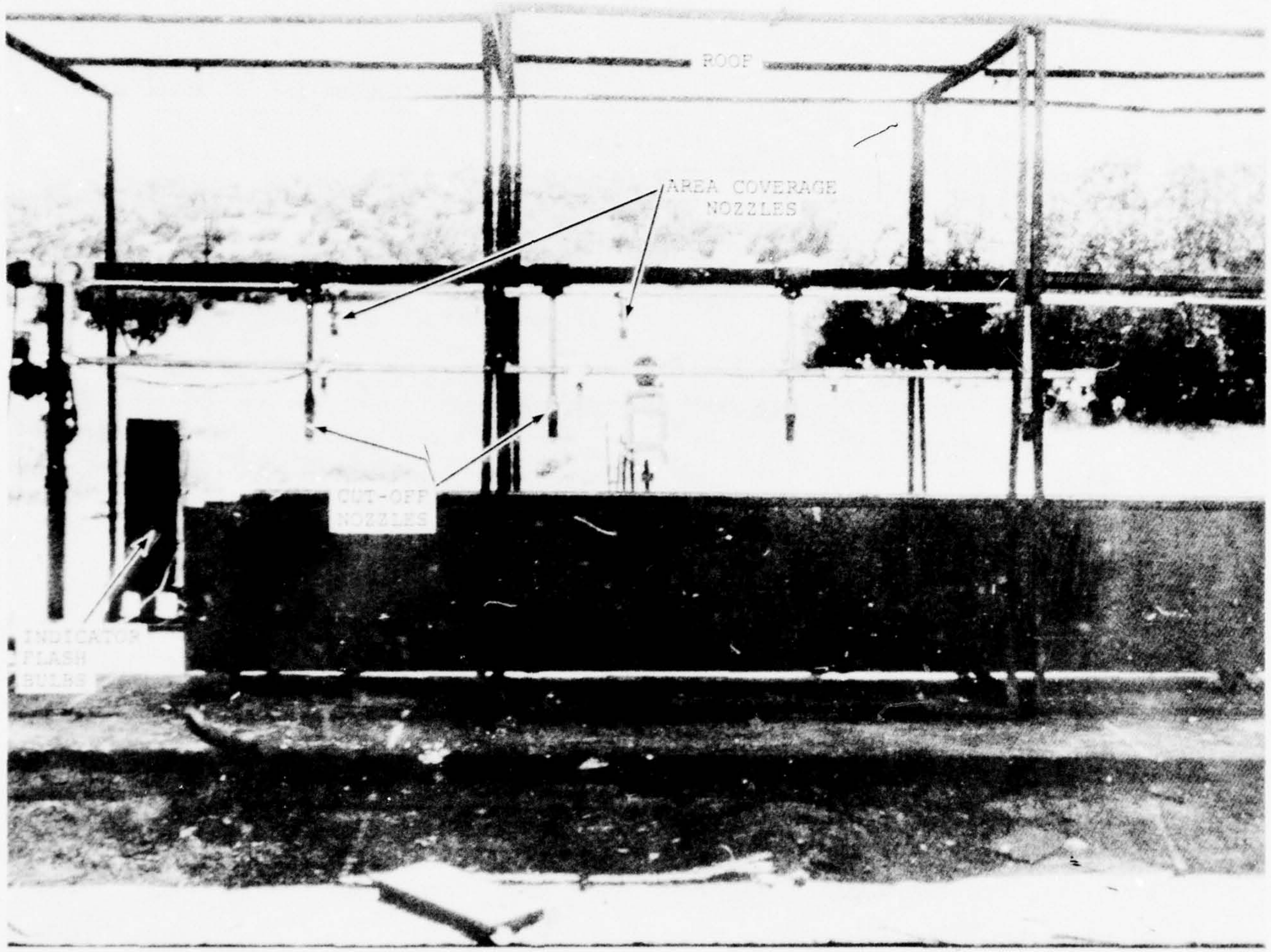


FIGURE 4. Side View Of Donor Accumulator And Deluge Nozzles

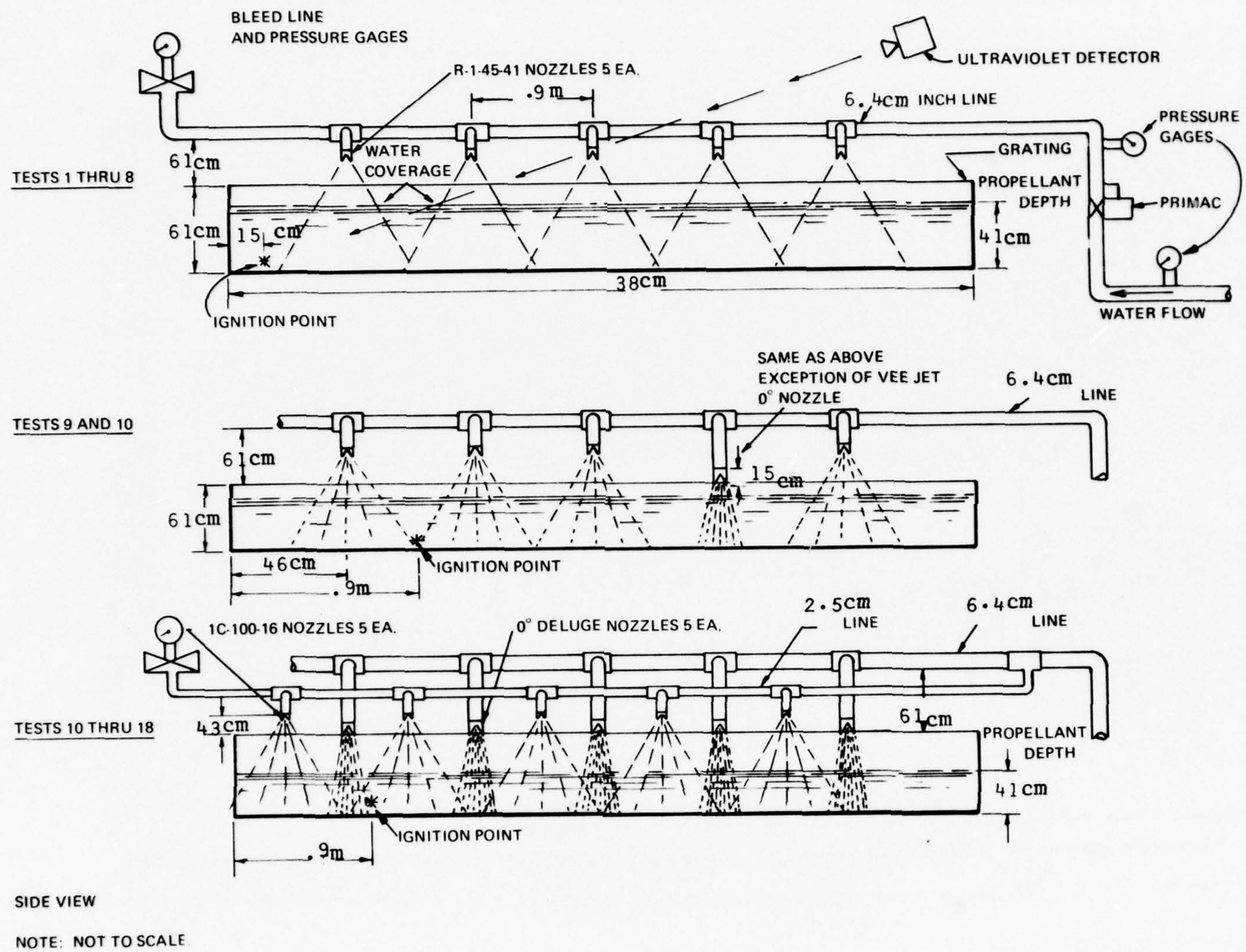


FIGURE 5. Three Variations Of The Indiana Accumulator Deluge System

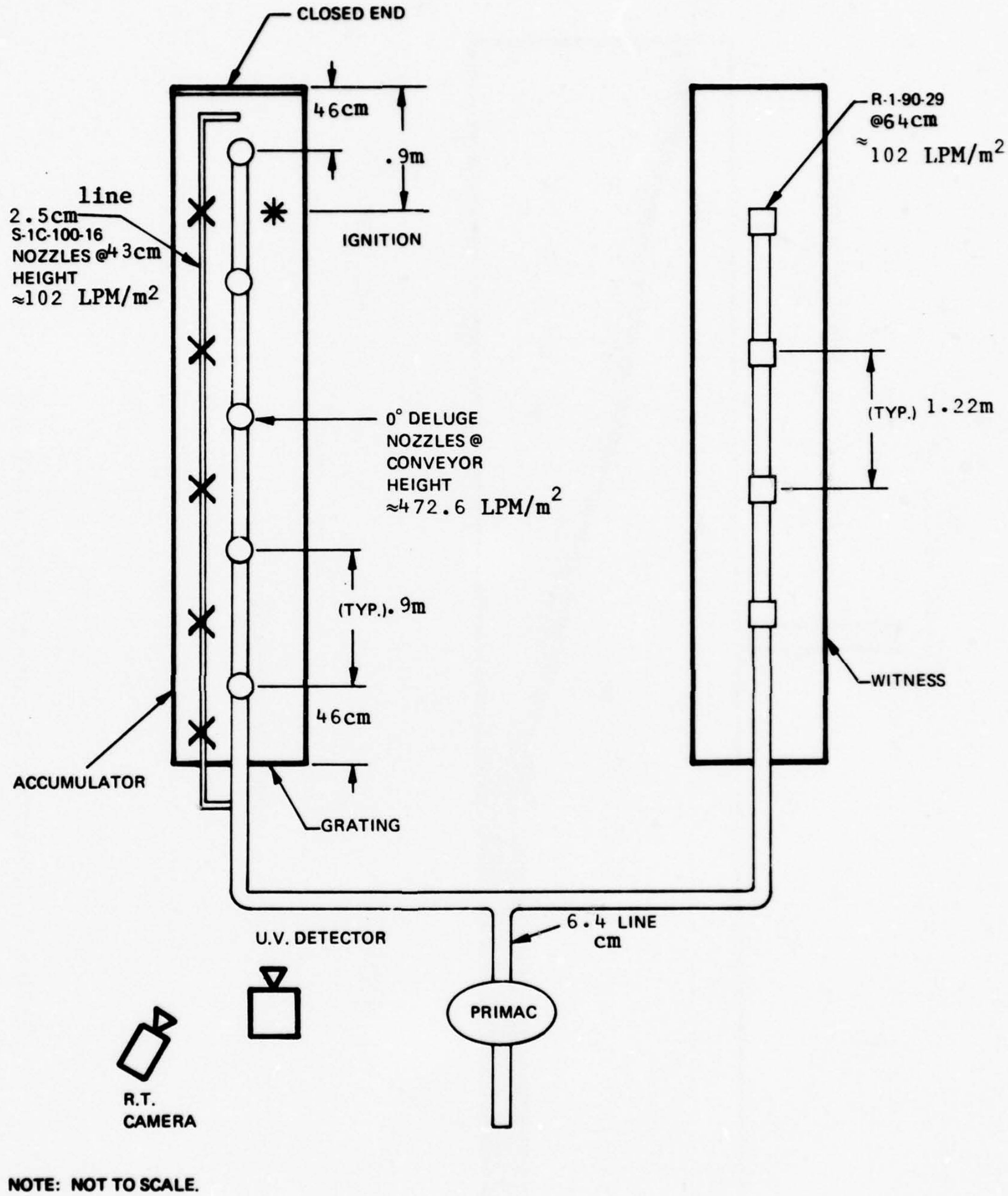
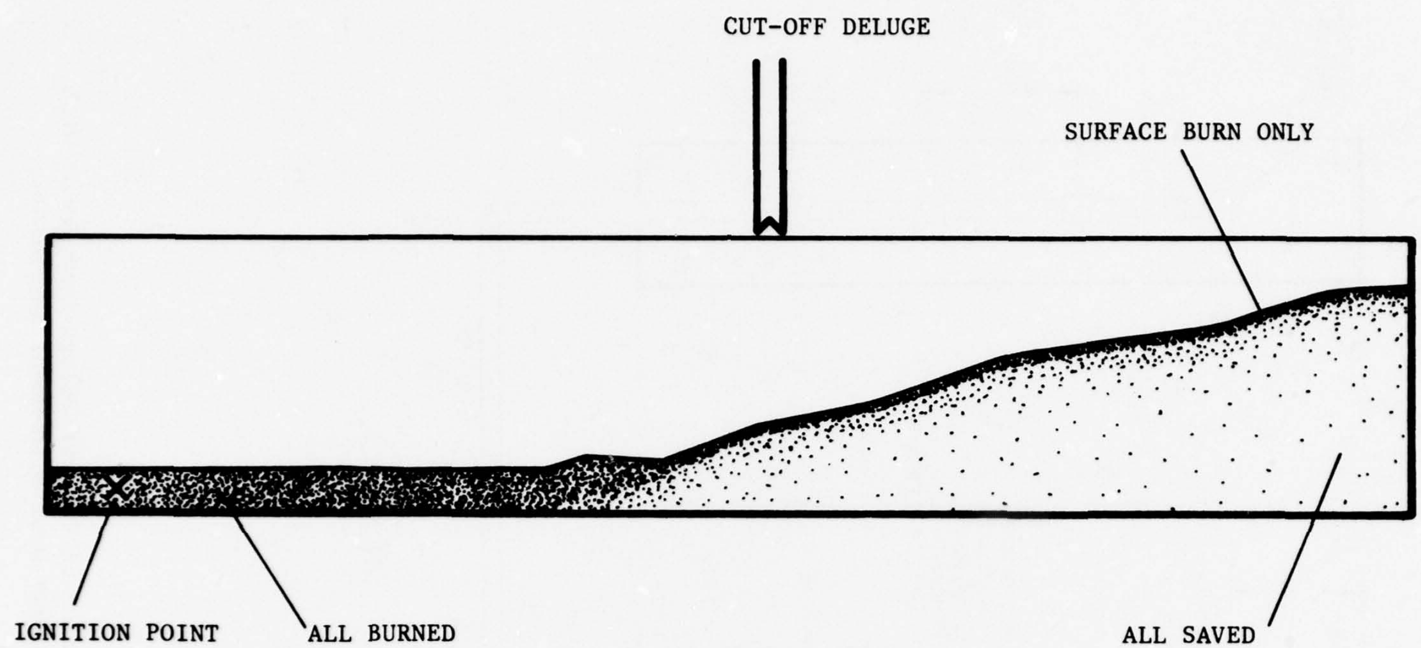


FIGURE 6. Illustration of Cut-Off Deluge Over Donor With Area Coverage Over Both Donor and Witness



DONOR ACCUMULATOR

FIGURE 7. Schematic Of Cut-Off Nozzle Function

deluge nozzle. Should ignition of the propellant bed occur, at the left of the figure, all of the propellant in the immediate vicinity of the bottom ignition would be burned prior to the detector sensing the fire at the surface. Hence, that portion of the accumulator propellant bed would be expended. The cut-off nozzle acts to separate the bagged propellant with the result that the propellant on the right hand side of the cut-off nozzle would suffer surface burning only. This could be rapidly extinguished by both the area coverage and also by the adjacent cut-off nozzle in the real life 21.3 m long accumulator. It was concluded from the experimental test firings that the fire could be totally contained within a distance of 2 m from the point of ignition.

To illustrate the functioning of the cut-off nozzle principle, Figure 8 shows the results of a typical test. Note that all of the bagged propellant at the end of the accumulator has been saved, while all of the propellant at the far end has been completely consumed. In the witness accumulator, only surface burning occurred, which was quickly extinguished by the area coverage nozzles and approximately 95 percent of the bagged propellant in the witness accumulator was saved. Figure 8 also illustrates the serious consequence of bottom ignition under 40.6 cm of bagged propellant. The generation of gas early in the fire, and prior to the detector being able to sense any surface burning, expands and causes an eruption of the total bed of propellant. This eruption throws burning bags of propellant out of the donor accumulator which are then deflected by the roof and fall all around the adjacent areas. Some of these bags are wetted down by the area coverage and are extinguished. Some fall into the adjacent accumulators and are extinguished by the area coverage over the witness conveyors, while some bags fall harmlessly to the floor and burn to completion.

A series of 18 test firings were conducted, including a set of preliminary tests to assess the functioning of an adequate water deluge system, followed by a set of confirmatory tests to prove the deluge design. It is important to realize that these confirmatory tests were made under restrictive conditions designed to duplicate as closely as possible the real life in-plant situation. These restrictions were as follows:

- Full-scale tests in a section of accumulator with the use of an adjacent or witness accumulator.
- A roof was placed over the test area to deflect fire brands into the witness accumulator.
- Bottom ignition was used.
- Detectors were placed to view the surface of the donor accumulator.
- Maximum static water pressure equaled 448 kPa.

FIGURE 8. View Of "Saved" Propellant After Test

Results

The total test program of the Indiana accumulator water deluge system consisted of 18 tests, the first 10 of which were categorized as being "preliminary", and Shots 11 through 18 were confirmatory shots. All 18 tests are listed in Table IV.

Propellant and Ignitor - For the test series, only bagged M-1 multi-perforated propellant was used (see Table I). In the donor accumulator, bag Nos. 3, 4, 6 and 7 were used interchangeably, while in the witness accumulator only bag No. 5 was used. The use of the No. 5 bags in the witness was an economic expedient, and since bag No. 5 has a metallic lining on one side of the bag, these No. 5 bags were carefully placed with the fabric side up so as to allow for ignition resulting from the fire brands falling on the surface of the witness accumulator. To ignite the bag propellant in the donor accumulator, a series of preliminary tests indicated that it would be necessary to use more than just an electric match to cause a positive ignition of the bagged multi-perforated propellant. These tests indicated that an electric match plus two grams of black powder inserted into a bag of multi-perforated propellant would effectively cause an intense ignition source; hence, this ignition was used throughout the confirmatory tests. The point of ignition was placed 15.2 cm from one end of the accumulator for the first six experiments. However, in order to simulate a random ignition point (ignition occurring at any point along the accumulator), all of the latter tests were ignited at a distance of three feet from the end of the accumulator.

Water Deluge System - The progression followed in the development of an effective water deluge system was shown schematically in Figure 5. The initial test firings quickly showed that the ignition point only 15.2 cm from the end of the conveyor was not a realistic situation, and also that the area coverage would not penetrate through the bagged propellant and extinguish a fire progressing along the bottom of the conveyor. Consequently, the principle of using the cut-off nozzle was adopted, resulting in the dual coverage system which was shown in Figure 6. It should be noted here that the choice of the nozzles used and the height that these nozzles were placed above the accumulator and witness trays was governed by the desired water coverage coupled with the allowable 448 kPa static water pressure. The designer of an in-plant system is cautioned to look primarily at the water coverage and at the static water pressures which are available, and using these two criteria, to design an effective plumbing system coupling the nozzles with the water supply line.

Sequence Timing of Events - For the test firings, the sequence of events was timed, both electronically and via the flashing of bulbs placed in view of the high-speed camera coverage as was described in Section II. The response times of the events were then averaged for all of the confirmatory test firings, and the results are reported in Table V Note that the confirmatory tests consist only of Tests 11 through 16, and for these shots the averages and standard deviations are shown. Also

TABLE IV

Summary Of Accumulator Test Firings

Test No.	Source & Location	Deluge	Recovery Accumulator	Recovery Witness	Comments	
1	EM + 20 g @ 15cm	Dry burn	N/A	N/A	Good test, 40 sec burn	
2	EM + 20 g @ 15cm	A-RI-45, 483kPa, @ 96cm	53%	87%	3:31 min burn, no fire at detector end	· Hi-pressure of #3 needed to cut bags
3	EM + .00006 g @ 15cm	A-RI-45, 620kPa, @ 61cm	86%	100%	41 sec total burn--no fire beyond 1.8m	· 61cm elev. of deluge is best
4	EM + 2 g @ 15cm	A-RI-45, 448kPa, @ 61cm	56%	100%	2:18 min burn--no fire at detector end	· .00006 g BP ignition is overkill
5	EM + .00006 g @ 15cm	A-RI-45, 448kPa, @ 61cm	48%	100%	2:4 min burn--fire came out detector end	· If 448kPa is max--based on #4 deluge must be redesigned
6	EM + .00006 g @ 15cm	A-RI-45, 448kPa, @ 30cm	43%	95%	4 min burn--no fire at detector end	
7	EM + .00006 g @ midpoint	4-RI-45, 448kPa, @ 61cm	57%	84%	1 min burn--violent fire	· Variation in % recovery between #7 & 8, and #9 & 10 may be due to MP ignition and random fire brands
8	EM + loose @ midpoint	4-RI-45, 448kPa, @ 61cm	32%	28%	0.64 min burn--violent fire after slow start; only 138kPa on witness	
9	EM + loose @ .9m	4-RI-45, 448kPa, + deluge @ 1.4m	59%	58%	0.87 min burn--no fire or smoke past deluge; 207kPa on witness	· Shots #9 & 10 designed to cut fire. #9 saved 90% aft of deluge and 43% fore of deluge.
10	EM + loose @ .9m	4-RI-45, 448kPa + deluge @ 1.4m	37%	41%	0.93 min burn--fire over entire accumulator	
11	EM + 2 g BP @ .9m	New design 2/5 smooth bore nozzles, 448kPa	69%	N/A	Fire stopped 1.22m from end of accumulator & witness. Both UV & IR used; I-Primac 1.4 sec. One witness nozzle blocked	
12	Repeat of Test #11		69%	69%	Fire stopped 1.52m from end of accumulator & witness. Both UV and IR used; I-Primac 1.3 sec.	· Cut-off deluge nozzle does penetrate bag depth of 41cm and stop under-burn.
13	EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26	58%	100%	Some fire over entire surface of accumulator. Deluge cut underburn.	· Some surface burning occurs, but longer accumulator would permit full extinguishment.
14	EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26 w/slight modification	53%	89%		· Fire stopped before end.
15	EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26 w/slight modification	59%	81%		
16	EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26 w/slight modification	53%	100%		
17	EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26 w/slight modification	42%	93%	#1 bags of single-perforated used.	
18	Top ignition EM + 2 g BP @ .9m	5-0° nozzles Witness: 4-RI-90-26 w/slight modification	63%	95%	Top ignition.	

TABLE V

Accumulator Timing Data
(All Time in Seconds)

Test No.	Test Type	Film Ignition-Primac	Scope Ignition-Primac	Film Ignition-Water On	Scope Ignition-Water On	Ignition-I.R. (Scope)	Ignition-U.V. (Scope)	Ignition-Exting.
1	Preliminary Tests	--		--				46.0
2		3.56		3.68				118.0
3		0.94		--				47.2
4		1.03		--				110.0
5		--		1.34				--
6		1.00		1.03				100.0
7		--		--				69.0
8		1.84		1.84				42.5
9		--		1.72				63.09
10		1.72		--				64.24
11	Confirmatory Tests	--	1.39	1.61	1.45	1.42	1.35	46.23
12		1.31	1.29	1.80	1.77	1.3	1.23	38.86
13		1.18	1.13	--	1.39	1.13	1.1	35.42
14		1.18	1.14	1.50	--	1.14	1.13	35.7
15		1.61	1.49	--	1.50	1.5	1.42	67.4
16		1.49	--	1.61	--	--	--	35.14
17	#1 Bags of M1-SP	0.575	0.59	0.575	0.6	0.6	0.5	52.96
18	Top Ignition	0.656	0.62	1.27	1.18	0.58	0.6	43.30
Averages (Nos. 11-16 only)		1.354	1.288	1.63	1.527	1.298	1.246	43.12
Std. Dev.		0.191	0.156	0.130	0.167	0.165	0.138	12.61

note the relatively long time between ignition and detection by either the IR or UV detectors (1.298 sec and 1.246 sec, respectively). This delay was caused by the bottom ignition and the time delay to burn through the top surface, at which point the detectors could sense the fire. Here, as in all other cases the IR was approximately 50 msec later than the UV in sensing the fire.

A detailed review of the timing data taken during the accumulator test firings shown in Table V will reveal that the time from ignition to the activation of the Primac valve was 1.288 seconds, 0.42 milliseconds after UV detection. This reflects the time required for the signal to pass from the detector through the amplifier and relays and send a trigger pulse to the primac valve detonators. The time from activation of the Primac valve to the application of water on the fire was 239.0 milliseconds (1.527-1.288). This time appears quite long considering that the water lines were preprimed and that the primac valve begins to open immediately following the release by the detonators. The delay is, no doubt, caused by the time required to move the water through the nozzles and to activate the mechanical water switch which was placed several inches in front of one of the nozzles.

For the confirmatory tests, shots 11 thru 16, an average time from ignition to full extinguishment is shown to be 43.12 seconds. This value was obtained in two ways, first by a stopwatch recording of the visual observation of the actual fire, and the second, by a more careful analysis of the high speed film. Due to the dense clouds of smoke caused by the burning propellant and the propellant bags, the precise time of extinguishment is very difficult to determine with any accuracy. Consider that, with bottom ignition, a vigorous fire is well under way before the application of water. Immediately upon application of water a dense white cloud is generated which is no doubt more steam than products of combustion, and this cloud obscures the visual observation. The fire was judged to be extinguished when this white smoke had receded to a bare minimum, and the surface of the unburned residue could be visually observed.

Temperature Measurements Surrounding Accumulator - Being able to extinguish a propellant fire is not always in-and-of itself sufficient to be considered a successful attack upon the fire and the resulting savings in property damage and human lives. It was of vital interest, therefore, that a knowledge be gained from the tests with regard to the temperature rise in the area surrounding the accumulators; this temperature rise, together with a knowledge of the ambient pressure rise, could then be translated into the probable extent of damage to the building structure of the room housing the seven accumulators. To monitor the ambient temperature rise, five temperature sensors were placed at 3.1 m intervals from 0 to 15.2 m on each side of the donor accumulator. The temperature sensors used were "Teletemp Recorders," which change color to reflect the maximum temperature felt at that point during the event. The Teletemp pellets were affixed to stakes driven into the ground and were set at a height of 1.2 m, with the individual pellets able to monitor temperatures from -17.8°C to 176.6°C. In no case was a temperature of 176.6°C exceeded.

Temperature measurements were made for six of the test shots, and the average temperature measured at each distance is given in Table VI. The standard deviations of each average temperature are seen to be rather large, the variation being due to the fact that these tests were conducted in the open air, and consequently, the direction of the wind or shifts in the wind caused a wide variation in the temperatures which were recorded. Using statistical analysis techniques, the average temperature ratio and the standard deviation of the ratio were calculated, and the resultant equation was plotted as shown in the graph at the bottom of Table VI. These temperatures, although severe, were existent for only a very short period of time, and it was judged that a surrounding structure, notably a concrete wall nearby an accumulator fire, would not be severely damaged by the rise in temperature. Hence, it would appear that the water deluge system was effective in extinguishing the fire prior to any significant rise in the ambient temperature.

Propellant Recovery - Still another measure of the success of the water deluge to extinguish an accumulator fire was that measured by the quantity of propellant recovered after each test. For the confirmatory tests, Shot Nos. 11 through 16, the propellant percent recovery data were given in Table IV, and it was seen that the average dry weight recovery of propellant in the donor accumulator was 60% and in the witness accumulator 88%. Attention is called to the fact that the value given for the percent recovery in the donor accumulator is that for the total mass recovered. Individual values of percent recovery fore and aft of the first cut-off nozzle could not be easily obtained. However, visual observation indicated that the recovery followed that which was shown schematically in Figure 7, wherein the propellant before the deluge nozzle was almost totally consumed, whereas the propellant aft of the deluge nozzle was almost totally saved.

For information purposes regarding water retention in the wetted down M-1 MP propellant, the average wet to dry ratio is given in Table VII.

Conclusions from Accumulator Tests

The full-scale tests of a water deluge system to extinguish an accumulator fire such as might occur at the Indiana AAP were most successful. The dual coverage water system, consisting of both the use of cut-off nozzles to penetrate the bags and extinguish the fire in the donor accumulator and the use of area coverage to extinguish extraneous fires which may occur in adjacent accumulators, was shown to be effective even with the restriction of 448 kPa static water pressure. The cut-off deluge nozzles provided 472.6 LPM/m^2, the area coverage nozzles provided 101.9 LPM/m^2, and the test demonstrated that the fire can be extinguished within 2m of the point of ignition. It was also demonstrated that with the exception of some small surface burning in the witness accumulator, any extraneous fire brands which fell into an adjacent accumulator could be extinguished by the area coverage, with the consequent result that the witness, adjacent accumulators, could be totally saved. Also of significance was the fact that, because of the rapid extinguishing of the donor

TABLE VI

Temperature Surrounding Accumulator

Distance from Accumulator (m)	Average Temperature 6 Shots (°C)	Standard Deviation
3.1 m	143.9	79.9
6.1 m	113.6	91.2
9.1 m	74.3	53.7
12.2 m	58.0	16.3
15.2 m	51.4	10.4

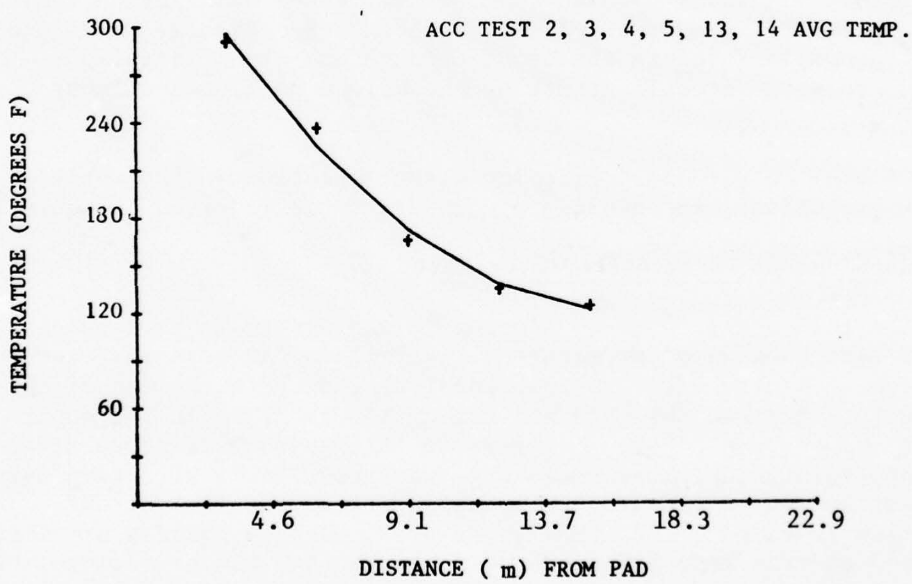


TABLE VII

Water Retention In Bagged M-1 Propellant

DONOR ACCUMULATOR

Test No.	Wet Weight, kg	Dry Weight, kg	Ratio W/D
2	274.9	251.3	1.09
3	414.6	386.0	1.07
4	245.0	220.9	1.10
5	235.4	212.3	1.10
6	268.5	192.3	1.39
7	240.4	182.3	1.31
8	181.0	146.1	1.23
9	316.1	293.9	1.07
10	216.4	187.0	1.15
11	387.4	344.7	1.12
12	310.7	294.8	1.04
13	289.4	306.2	1.09
14	290.3	230.9	1.11
15	353.0	331.1	1.06
16	313.0	288.5	1.08
17	289.0	201.4	1.43
18	374.0	341.1	1.09
		Average	1.148
		Std. Dev.	0.118

accumulator fire, there was only a relatively small rise in the ambient temperature, not sufficient to cause any significant damage to the concrete walls surrounding the accumulator room at the Indiana AAP. Lastly, another important conclusion was drawn from the test series: In no case was there any evidence of the fire in the propellant transcending into a low order or high order detonation. Consequently, any accumulator fire that should occur in the Indiana AAP can be considered as a Class 1.3 hazard rather than a possible Class 1.1 hazard.

Indiana Hopper Tests

Discussion

A potential bottom ignition of a large quantity of M-1 single perforated propellant stored in hoppers posed another unique fire extinguishment problem at the Indiana AAP. These hoppers receive loose propellant from an airveyor coming down through the roof, and the main concern is limiting the amount of propellant burn should a fire occur. An uncontrolled fire in this quantity of propellant could transcend to a detonation or can produce intense heat radiation, thus causing severe damage to the hopper, to the immediate building structure, and to production machinery.

The most immediate concern was to determine whether large quantities of propellant contained in an open hopper would transcend into a detonation if and when a fire occurred. To answer this question, a series of seven exploratory tests were conducted in which varying weights of loose M-1-SP propellant were placed in an open hopper and ignited at the bottom of the propellant bed. The results of these seven exploratory tests are shown in Table VIII. The first of these exploratory tests was conducted using 113.4 kg of propellant without the application of a water deluge system. Obviously, all of the propellant burned, but most important, the deflagration did not transcend into a detonation. For the succeeding six exploratory tests, a simple water deluge was used, a deluge employing a rather slow opening solenoid water valve and water lines which were not preprimed prior to the shot.

The results of these tests clearly indicated that a large propellant fire occurring in a hopper could be retarded and eventually extinguished with the rapid application of water, and that through future testing, the water deluge system could be significantly refined to control even larger hopper fires. Exploratory Test No. 6 led to the conclusion that 621 kPa was more effective than 414 kPa, however since 448 kPa was the maximum allowable at the Indiana AAP, a water deluge system probably could be designed to handle large hopper fires within the allowable static water pressure limit. To test these hypotheses and to evaluate the effectiveness of an improved deluge system, SwRI, under the sponsorship of ARRADCOM, undertook the series of tests to be described in this report.

As in the case of the accumulator problem, the bed depth and time to propagate a fire through the propellant bed were factors that

TABLE VIII

Summary of Exploratory Hopper Tests

Shot/Type	Total Weight of Loose M-1 Propellant (kg)	Static Water Pressure (kPa)	SwRI Nozzles Used	Mass Recovered (kg)	% Recovery
1	113.4	DRY BURN	DRY BURN	-	-
2	45.3	448	2	2.04	5
3	90.7	448	3	27.2	30
4	136.1	448	3	26.5	20
5	181.4	448	3	42.2	23
6	90.7	621	3	35.8	40
7	90.7	448	3	33.6	37

Notes: No detonations in any test.
Fire was estinguished with some recovery in every test, except No. 1
Hopper not bent, warped, etc.
Water lines were not preprimed.
Slow opening solenoid water valve used, except in No. 1

complicated a sensor's ability to detect a fire. Again, because ultraviolet and infrared detection systems are fast responding, both were used for this study. A deluge system was designed to fight these hopper fires as shown schematically in the artist's sketch in Figure 9. Teletemp gauges were used at 3 m intervals on each side of the hopper to record the ambient temperature rise. The hopper, in the Indiana plant, actually is projected up to and out of a port in the roof of the building. Any fire in the hopper would cause fire brands to erupt from the hopper and out through the roof, but this action is not considered a fire hazard because the roof of the building is reinforced concrete and, hence, is nonflammable. This setup is depicted in a second artist's sketch as shown in Figure 10.

For the test program, a hopper was constructed of 0.31 cm thick mild steel, and the water deluge system was designed to project down into the top of the hopper, as shown in Figure 11. For the test series to be described herein, the roof on the building was eliminated, and the fire brands that erupted from the hopper were merely allowed to fall back to the ground. Bottom-ignition burn tests were conducted with 181.4 kg and 453.6 kg of loose M-1 SP in the hopper.

For a design of the water deluge system, a water restriction of 448 kPa static water line pressure was again a limiting factor imposed upon the solution of this problem. For water coverage, a four-nozzle system providing 407.4 LPM/m^2 was positioned directly above the propellant. The effective water coverage can be seen in the schematic drawing of Figure 12. Here again, penetration through loose propellant with large quantities of water to prevent fire spread was the major consideration given to this design. Note in Figure 12 that the propellant level for the 181.4 kg test was 68.6 cm, and for the 453.6 kg test the level was 83.8 cm. Each of these propellant levels is in excess of the maximum height of 45.7 cm allowed by the AMC Safety Manual. Using bottom ignition, a major concern of the test program was the transition from deflagration to detonation of the M-1 SP propellant contained in the hopper. In descending order of concern, should no detonation occur, was the extinguishment of the fire before the hopper was warped or ruptured, and ultimately the extinguishment of a fire before any structural damage was done to the concrete building housing the receiving hopper.

With the side lowered on the receiving hopper, Figure 13 clearly shows the area coverage of the water deluge system, and Figure 14 shows the hopper loaded with 453.6 kg of M-1 SP propellant just prior to test.

The test series consisted of firing a number of preliminary tests to evaluate the techniques of assuring good, strong, positive ignition and to evaluate several variations of the proposed water deluge system. For these preliminary tests and for purposes of economic expedience, a number of tests were run with multi-perforated propellant. However, the critical confirmatory tests were run with the single perforated M-1 propellant. The confirmatory tests to demonstrate the water deluge

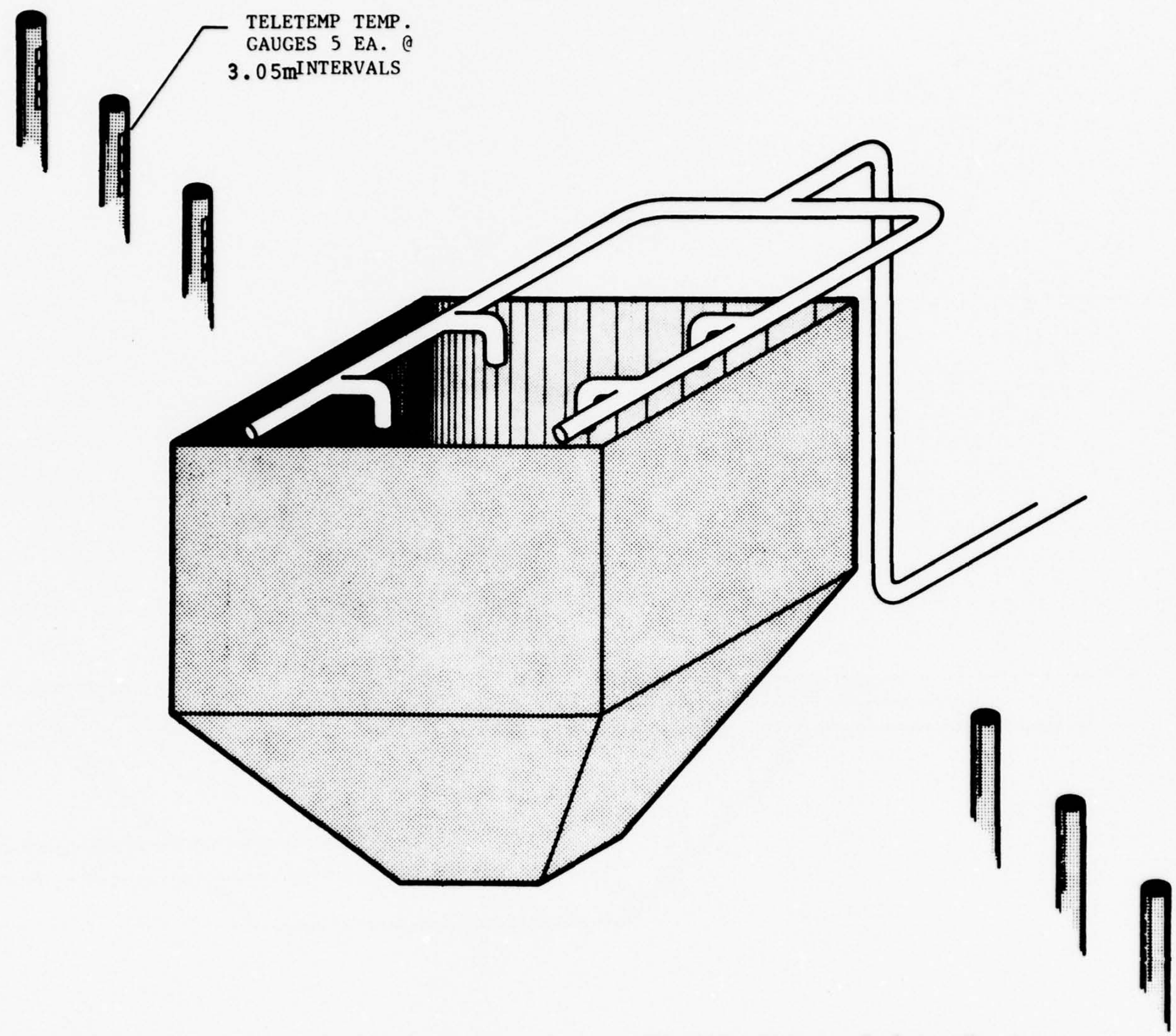


FIGURE 9. Schematic Design Of Water Deluge System Used In Hopper Deluge Tests

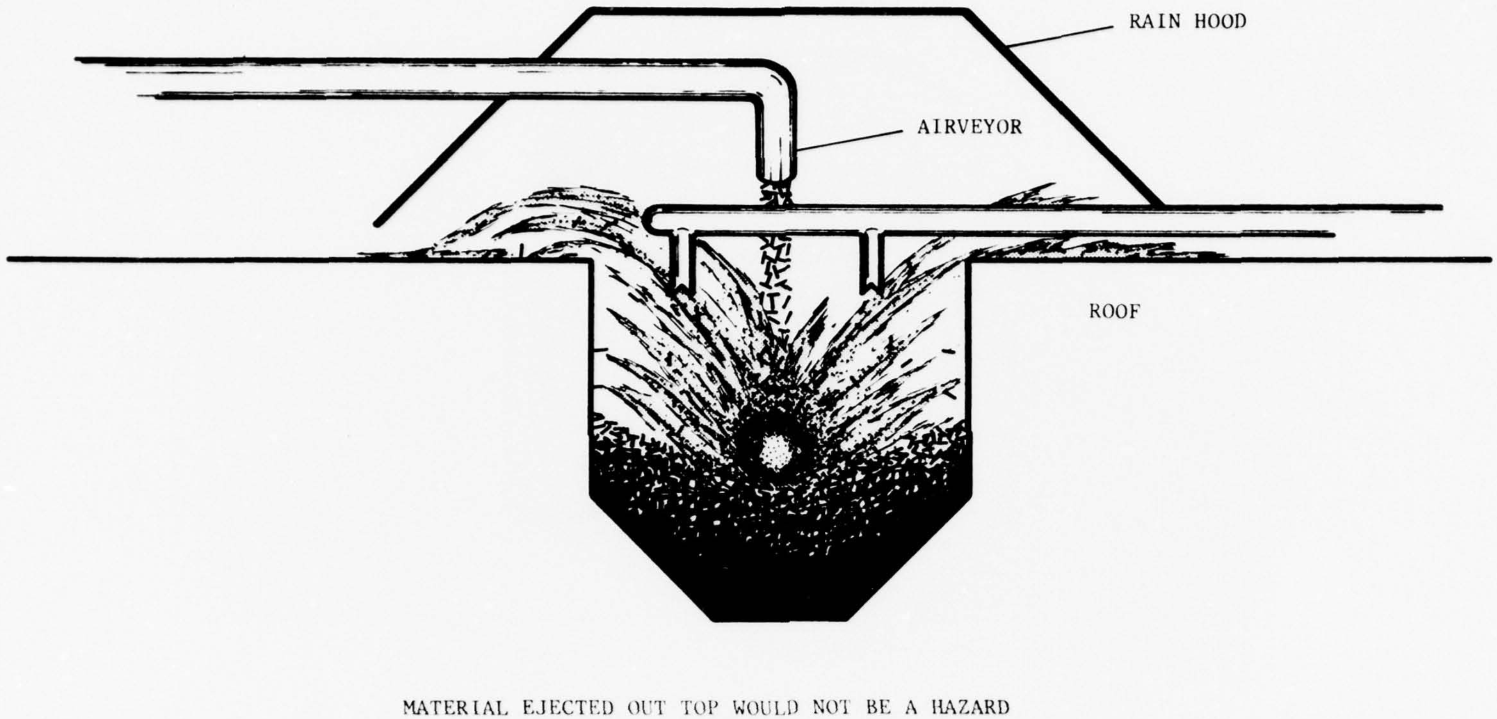


FIGURE 10. Sketch Of Hopper And Roof Layout

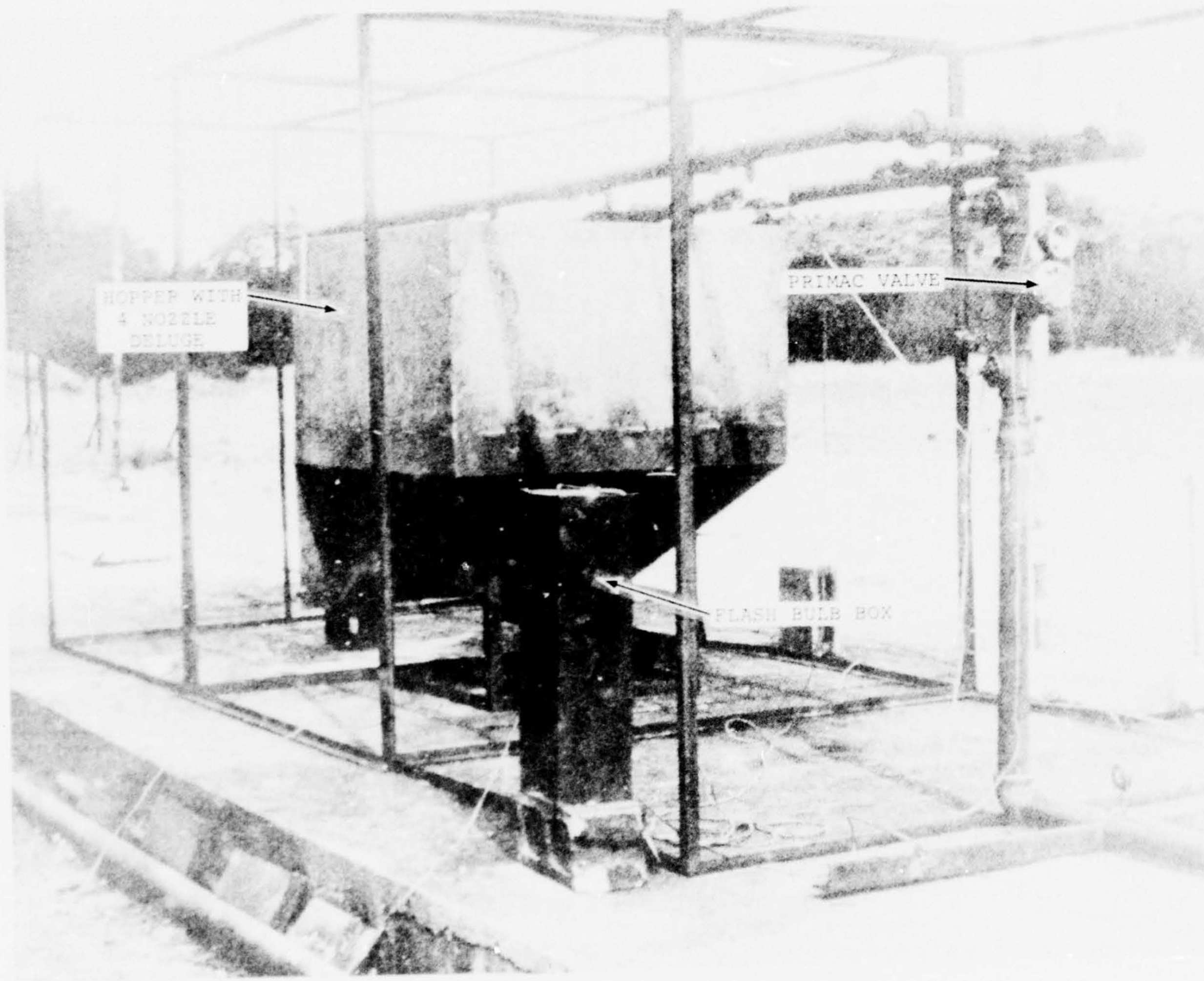


FIGURE 11. Photo Of Hopper Test Setup

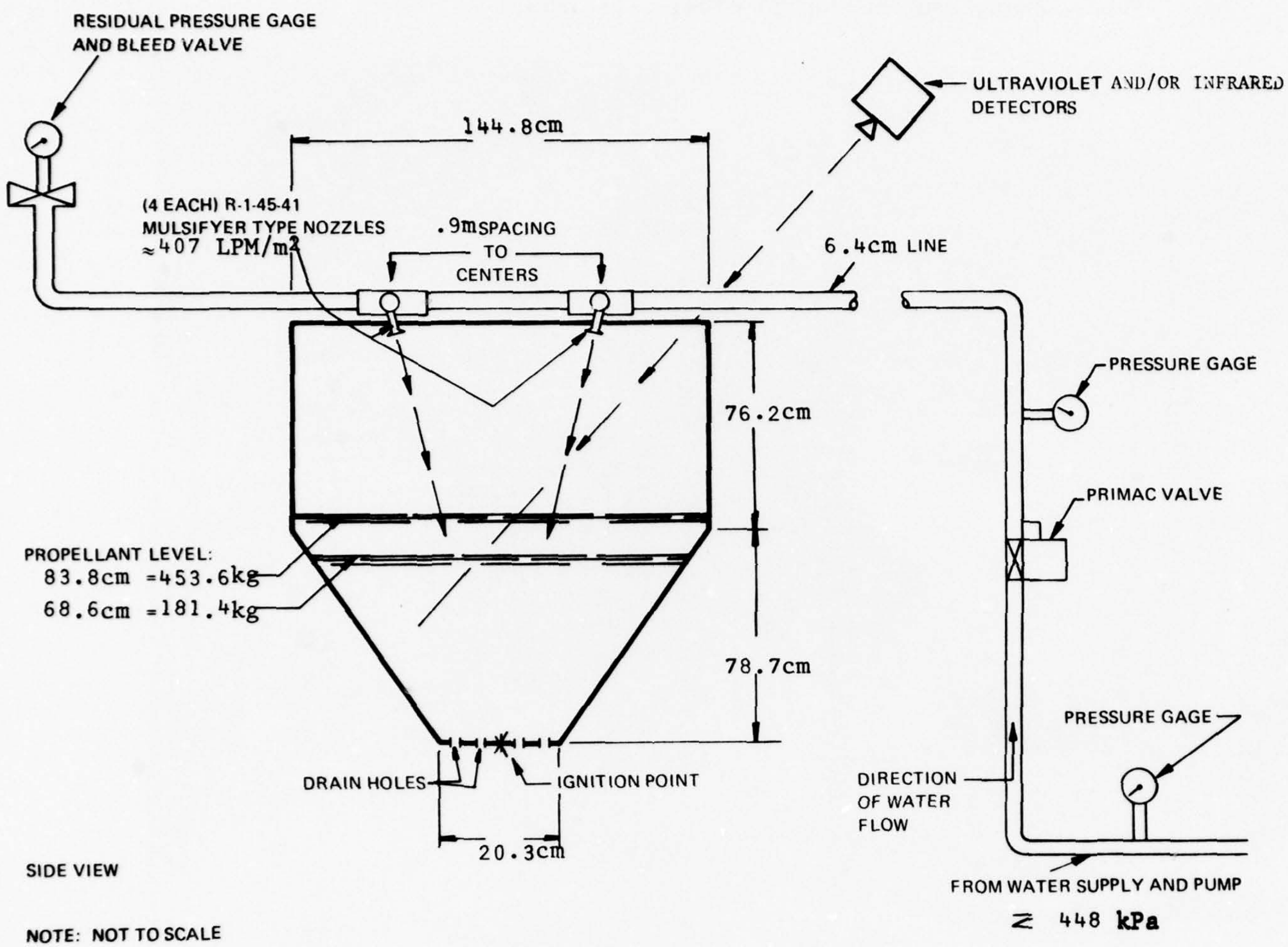


FIGURE 12. Schematic Of Hopper Deluge System

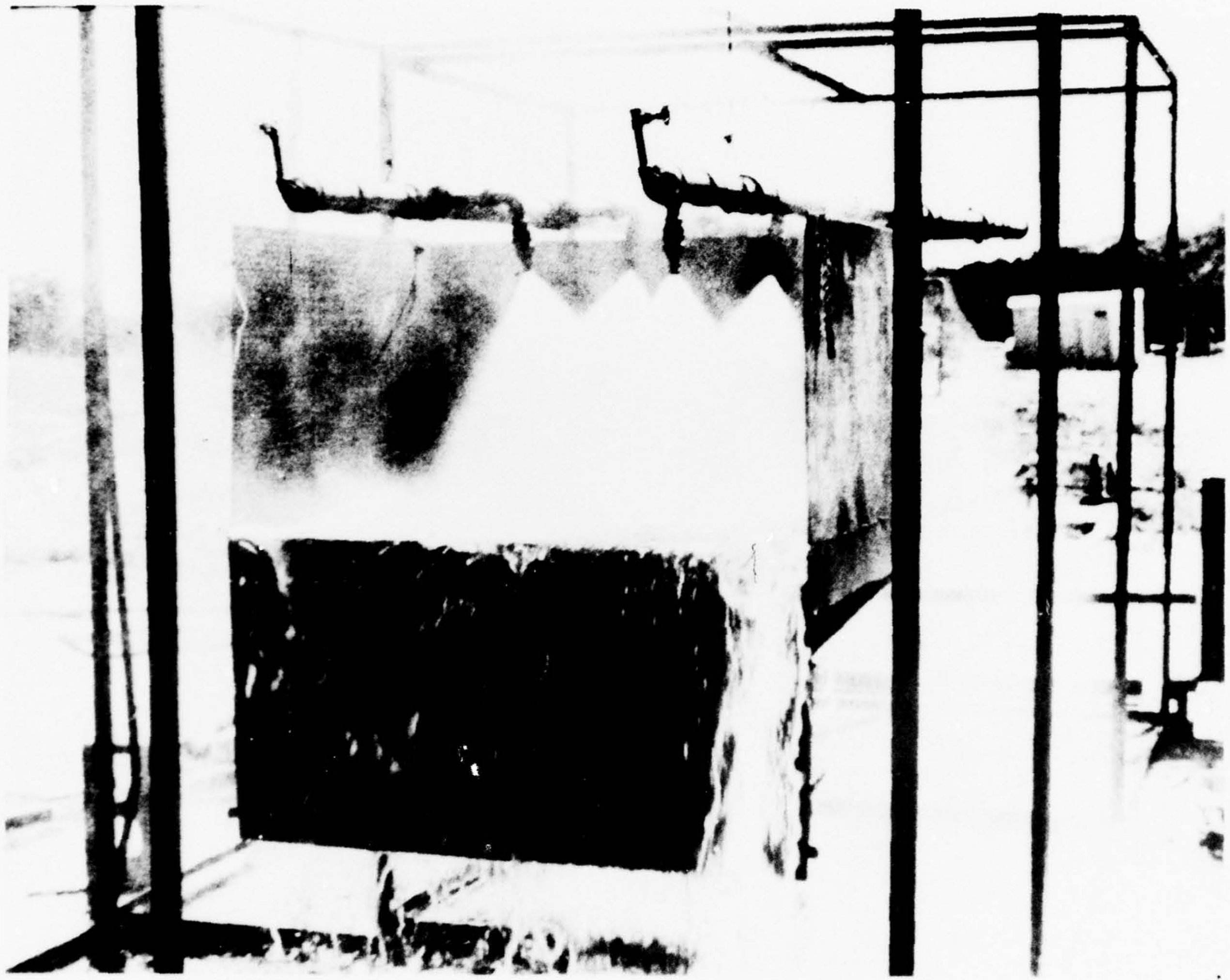


FIGURE 13. Side Of Hopper Lowered To Show Deluge

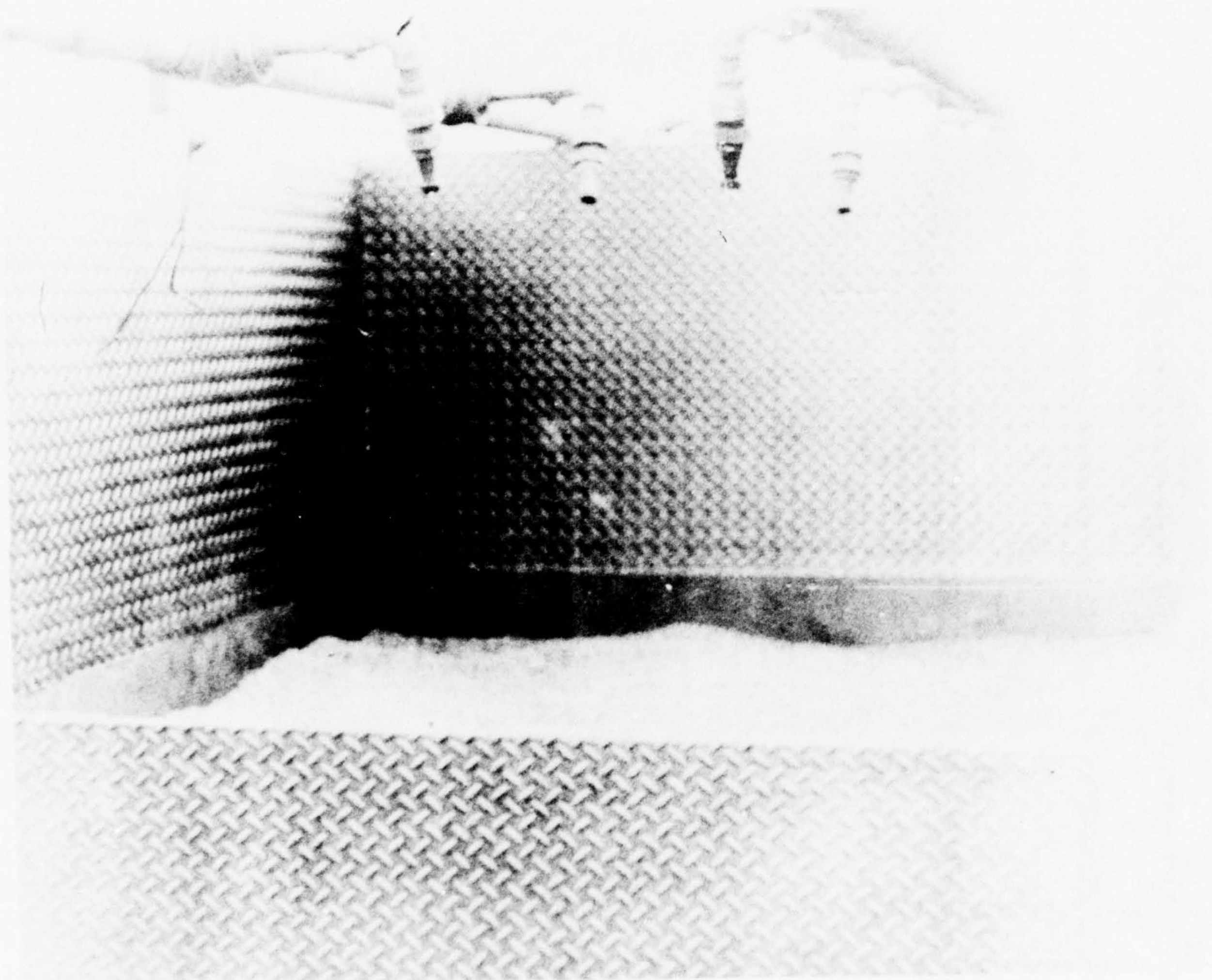


FIGURE 14. Hopper Loaded With 453.6 kg M-1 SP Propellant

system were made under restrictive conditions designed to duplicate as closely as possible the real life in-plant situation. These restrictions were as follows:

- Full-scale tests with 181.4 kg or 453.6 kg in a receiving hopper
- Detectors located to view only the top surface of the loaded hopper
- Bottom ignition in all cases
- Maximum static water pressure 448 kPa

Results of Hopper Tests

The total test program of the Indiana AAP hopper consisted of 18 tests, 12 of which were preliminary shots. The results of these, plus the six confirmatory shots, are given in Table IX. Containment of each propellant hopper fire was achieved within approximately 17 seconds. Although a maximum of only 70 percent propellant recovery resulted, the deluge system was considered adequate because in no case was the hopper itself damaged in any way, and all of the erupting fire brands were ejected out the top into a non-hazard area. The view of the fire approximately five seconds after ignition can be seen in Figure 15. The fire brands erupting from the top of the hopper can be seen reaching 6.1 m in the air, and this burning propellant would have fallen back down onto the concrete roof at Indiana and would have been of no concern.

Table IX presents the results of all 18 shots in the order in which they were fired. Note, however, that shots 11 thru 16 were considered to be the confirmatory tests to evaluate the effectiveness of the water deluge system. Tests 11 and 12 were conducted using the multi-perforated M-1 propellant, and consequently, to ignite this charge the electric match was boosted with 2 grams of black powder. In tests 13 thru 16, the single perforated propellant was tested, which required only the electric match for ignition. The single perforated propellant burns much more rapidly than does the multi-perforated propellant, therefore as a general rule, less propellant will be recovered in the single perforated tests than in the multi-perforated tests. This fact is borne out by the recovery shown in Table IX, approximately 62 percent recovery for the multi-perforated and 43 percent recovery for the single perforated propellant.

Test Nos. 10, 17, and 18 were conducted with 453.6 kg of M-1 propellant in the hopper. Although huge fires resulted from the bottom ignition of this large quantity of propellant, in no case was the hopper damaged in any way by the fire, and obviously no detonations occurred. With bottom ignition (83.8 cm below the top surface), the gas generated causes the entire mass of propellant to heave with the resultant violent eruption of material out of the hopper. This material is carried aloft by the propellant gases in the form of both burning propellant as well as unburned propellant. As noted earlier, this material in the plant

TABLE IX

Summary of Hopper Test Firings

Test #	Ignition	Location	Deluge	Static Pressure	Residual Pressure	Propellant Burned *	Wgt	Recovery	Comments
1	E.M.	Bottom	4-R-1-45-41	$3.5x10^5$Pa	$3.5x10^5$Pa	#2 Incr.	1779N	19.5%	Violent Burn with Violent Eruption throwing Burning Bags our of Hopper & Area of Deluge. Water on Immediately-Indication of Ground Loop Causing Premature Firing of Primac.
2	E.M.	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	68%	
3	E.M.	Bottom	4-F-1-45-41	$4.48x10^5$Pa		MP	1779N	N/A	EM failed to Ignite Propellant-Premature Water. Confirmed Concern About Ground Loop in Test #2.
4	E.M. w/2 g BP	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	43%	Violent Eruption of Flame Which Immediately Engulfed Almost the Entire Covered Area.
5	E.M. w/2 g BP	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	50%	Reaction Almost Identical to Test #4. Most of Burn Outside of Hopper.
6	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	1779N	22%	SP Fire Much More Violent Than MP Fire. Most of Burn Was Outside of Hopper.
7	Same As Shot #6							22%	Same as Shot #6.
8	E.M. + 2 g BP	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	51%	Modified Hopper w/High Sides-Results similar to Shots 4 & 5.
9	E.M. + 2 g BP	Bottom	Only 2 Nozzles	$4.48x10^5$Pa		MP	1779N	38%	Only 2 Nozzles Used-Note Difference In Recovery
10	E.M. + 2 g BP	Bottom	4-F-1-45-41	$4.48x10^5$Pa		MP	4450N	27%	Huge Amount of Propellant Thrown Out of Hopper.
11	E.M. + 2 g BP	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	64%	Confirmatory Shots - Compare w/8, then to 4 & 5 w/low sides
12	E.M. + 2 g BP	Bottom	4-R-1-45-41	$4.48x10^5$Pa		MP	1779N	60%	
13	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	1779N	40%	Confirmatory shots w/M-1, SP Propellant. Compare w/#6 w/low sided hopper.
14	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	1779N	42%	
15	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	1779N	48%	
16	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	1779N	43%	
17	E.M. Only	Bottom	4-R-1-45-41	$4.48x10^5$Pa		SP	4450N	21%	Difference in recovery due to top(20.32 cm diam) ignition on Test 18.
18	E.M. Only	Top	4-R-1-45-41	$4.48x10^5$Pa		SP	4450N	40%	

*MP = multi-perforated M-1 propellant
SP = single-perforated M-1 propellant

FIGURE 15. View Of Hopper Fire 5 Seconds After Ignition

situation would be ejected out onto the roof of the building and would cause no harm. In this test program, the material fell back onto the ground and burned in the area surrounding the hopper.

Test No. 18 is particularly interesting to this discussion since ignition was caused to occur at a point 20.3 cm down from the surface of the material, rather than at the bottom of the hopper as in all previous tests. With ignition relatively close to the surface, the time to detection was approximately 30 percent less than for the bottom ignition Obviously then, the detectors were able to sense the fire much quicker, activate the water deluge in a significantly shorter time, and the quicker application of water resulted in a significantly larger percentage of propellant recovered.

More detail concerning the experimental techniques and the test results will be discussed in the following paragraphs.

Propellant and Ignitor - The objective of this test program was to design and evaluate a water deluge system capable of extinguishing propellant fires which may occur in a receiving hopper containing large quantities of M-1 single perforated propellant. For expediency and for economic reasons, a number of the preliminary tests (shots 1 thru 12) were fired using the multi-perforated M-1 propellant, and for these tests an ignitor charge consisting of an electric match plus 2 gms of black powder was often used. For the confirmatory tests (shots 13 thru 18) the single perforated propellant was easily ignited with the use of only an electric match. In every test, with the exception of shot 18, the ignition point was at the center-bottom of the hopper. In test 18, the ignition point was 20.3 cm down from the top surface of the propellant and this test was fired for comparison purposes only. The bottom center ignition point was selected since it is at this point that the hopper door at the Indiana facility is located, and it is here that the safety analysis concluded that ignition could possibly occur. Bottom ignition represents the most extreme case from the standpoint of a fire hazard since the fire must burn through the entire hopper before reaching the top surface, at which point the detectors can sense and react to the fire. The time delay in sensing the fire imposed by bottom ignition will be discussed later.

Water Deluge System - A water deluge system, shown in Figure 12, consisting of four nozzles designated R-1-45-41 (see Table II for details) was used throughout these tests. This system provided uniform coverage over the entire surface of the hopper, and at the same time was compatible with the 448 kPa allowable static water pressure. These four nozzles provided water coverage which was both measured and calculated to be 407.4 LPM/m^2.

Sequence Timing of Events - For the test firings, the sequence of events was timed both electronically and via the flashing of bulbs placed in view of the high speed camera as has been described in Section II of this report.

A complete review of the timing data obtained for the 18 hopper test shots is given in Table X. Here again, we see that tests 1 thru 9 were fired as preliminary shots to evaluate the functioning of the water deluge system and to prepare the electronic recording apparatus. Tests Nos. 10, 17 and 18 were fired using 453.6 kg of propellant in the hopper and the sequential timing of events for those three shots can be visually compared. Tests Nos. 11 thru 16 were fired as "confirmatory" tests and the averages and standard deviations of those data are given in the table. Referring to these average values, several significant observations can be made. It should first be noted that it took an average of 1.096 seconds for detection of the fire by the UV detector. The IR detector responded soon thereafter, for a lapsed time from ignition to detection of 1.156 seconds. Here again, on the average, the IR detector responds approximately 50 msec later than does the UV detector. Note also that the response time of the UV was approximately one full second after ignition. This response time is governed primarily by the time it takes for visible flame to reach from the bottom of the hopper to the propellant surface bed, at which time the fire is exposed to the detector.

In Section II, Figure 1, the event timing network was described in detail. From that timing network and referencing the data in Table X, it can be seen that it required 56 msec from UV detection to the ignition of the Primac valve detonators. This value, as recorded on the oscilloscope, is that time as measured between points D_O to H_I in Figure 1. We see also that the time from the activation of the Primac to the activation of the water switch indicating that water has been applied to the fire is approximately 380 msec. This time appears to be quite long, considering that the lines were preprimed and that the Primac begins to open the instant that the detonators are actuated. It must be recalled, however, that the "water-on" switch is a mechanical switch located approximately 15.2 cm in front of one of the nozzles and is mechanically actuated by the impact of the water being released.

Attention is also called to the recorded average time of 17.35 seconds from ignition to full extinguishment of the fire. This value is determined in two ways: first, a stopwatch is used while visually observing the actual test firing, and second, the burn time is more accurately measured from the high speed camera records. Both of these techniques are, however, not too accurate since the water deluge acts to quench the fire almost immediately and consequently the still-burning fire is obscured by dense clouds of white smoke and steam being emitted from the hopper. The fire is judged to be completely extinguished when this smoke has receded to a bare minimum. The recorded time to full extinguishment is, therefore, a very conservative number, since in all probability the remaining propellant grains have been wetted down to a degree that the fire was effectively extinguished in a shorter time than that shown in Table X.

Temperature Measurements Surrounding the Hopper - The first and most important observation to be made in the test firings was whether or not a fire contained within these large quantities of propellant would transcend from a deflagration to a detonation. After the first preliminary

TABLE X

Hopper Timing Data
(All Times in Seconds)

*Ignition 20.32 cm Down
From Top...All other Tests
Use Bottom Ignition (63.5 cm)

Test No.	Test Type	Film Ignition-Primac	Scope Ignition-Primac	Film Ignition-Water-On	Scope Ignition-Water-On	Ignition-IR(Scope)	Ignition-UV(Scope)	Ignition Exting.
1	SP-1779N							
2	MP-1779N							16
3	MP-1779N							--
4	MP-1779N		0.86				0.3	12.1
5	MP-1779N							13.55
6	SP-1779N	1.04						15
7	SP-1779N	1.15						13.55
8	MP-1779N	--	1.12		1.58		1.09	--
9	MP-1779N	0.805	0.65	1.38	1.19		0.62	21.4
10	MP-4450N	1.01	0.89	1.61	1.39		0.86	21
11	MP-1779N	1.22	1.12	1.91	1.75	1.09	1.09	13.65
12	MP-1779N	1.31	1.28	1.64	1.8	1.26	1.13	14.79
13	SP-1779N	1.19	--	1.26	--	--	--	18.9
14	SP-1779N	1.11	1.06	1.47	1.43	1.1	1.02	18.24
15	SP-1779N	1.08	1.05	1.34	1.25	1.06	1.02	19.82
16	SP-1779N	1.25	1.25	1.56	1.43	1.27	1.22	18.57
17	SP-4450N	1.21	1.15	1.21	1.18	1.25	1.1	21
18	SP-4450N	0.788	0.77	0.854	0.83	0.81	0.73	33.03
Avg.'s of #'s 11-16 only		1.19	1.152	1.531	1.532	1.156	1.096	17.35
Std. Dev.		0.086	0.107	0.230	0.234	0.101	0.083	2.49

shot, concern was with the rise in temperature and pressure in the area immediately surrounding a fire in a receiving hopper. Since our tests were conducted in the open field, the estimation of pressure rise had to be done analytically, as discussed in Appendix A of this report. To measure the temperature in the immediate area, a series of Teletemp pellets were placed at 3.05 m intervals on each side of the hopper. Temperatures were monitored on five of the test firings, and the averages of those recorded temperatures are shown both tabulated and plotted in Table XI.

It must be pointed out here that the temperatures were measured in the open air at various distances from the hopper and do reflect the heat radiation from the material which was ejected out of the top of the hopper and fell back to the ground in the area surrounding the hopper. In the real life situation, that material would have been ejected out through the roof and would have fallen back down onto the roof, thus, being of no concern. Consequently, these recorded temperatures shown in Table XI are given for information purposes only and do not necessarily reflect the true temperature rise outside the hopper at the Indiana facility. Nonetheless, the temperature rise is sufficiently small that it was judged that no significant damage would be caused to the hopper room at Indiana.

Propellant Recovery - As in the case of the earlier accumulator test fires, an important measure of the success of the ability of the water deluge to extinguish hopper fires was that measured by the quantity of propellant recovered after each test. Hopper test No. 1 was a dry burn, consequently, no propellant was recovered. The weightsof recovered propellant for tests 2 thru 18 are given in Table XII. Here we see a comparison of the weight of the wet propellant to the weight of the dry propellant, and the ratio of those weights. The wet to dry ratio averaged 1.156, indicating that the wet propellant retains approximately 16 percent water.

Conclusions to Hopper Tests

The full scale tests of a water deluge system used to extinguish a large hopper fire such as might occur at the Indiana AAP were most successful in that they demonstrated that no detonations would occur, nor would there by any failures of the hopper structure itself. In all cases it was shown that the fire could be quenched rather quickly and that full extinguishment could be effected within a period of approximately 10 to 17 seconds. Also of great importance was the demonstration that the water deluge system could be made to operate within the water pressure of 448 kPa and of the water adequacy provided by the Indiana plant.

The four nozzle deluge provided an application rate of 407.4 LPM/m^2 in a uniform pattern over the surface of the propellant bed in the hopper. This water deluge could be activated with either the UV or the IR detector, although it was shown that the UV detector does function approximately 50 msec before the IR detector. Total times from ignition to detection were approximately 1.0 second, controlled primarily by the constraint of

TABLE XI

Temperature Rise Around Hopper Fire

DIST.	OBS T	CAL T	RESIDUAL	RATIO
10.00000	335.00000	339.75556	-4.75556	1.01420
20.00000	258.00000	245.40000	12.60000	0.95116
30.00000	170.00000	179.26667	-9.26667	1.05451
40.00000	141.11111	141.35555	-0.24444	1.00173
50.00000	133.33333	131.66666	1.66667	0.98750

TEMPERATURE EQUATION

T = 462.3333 + -13.6689*D + 0.1411*D↑2

AVG RATIO = 1.00182
STD DEV OF RATIO = 0.03775

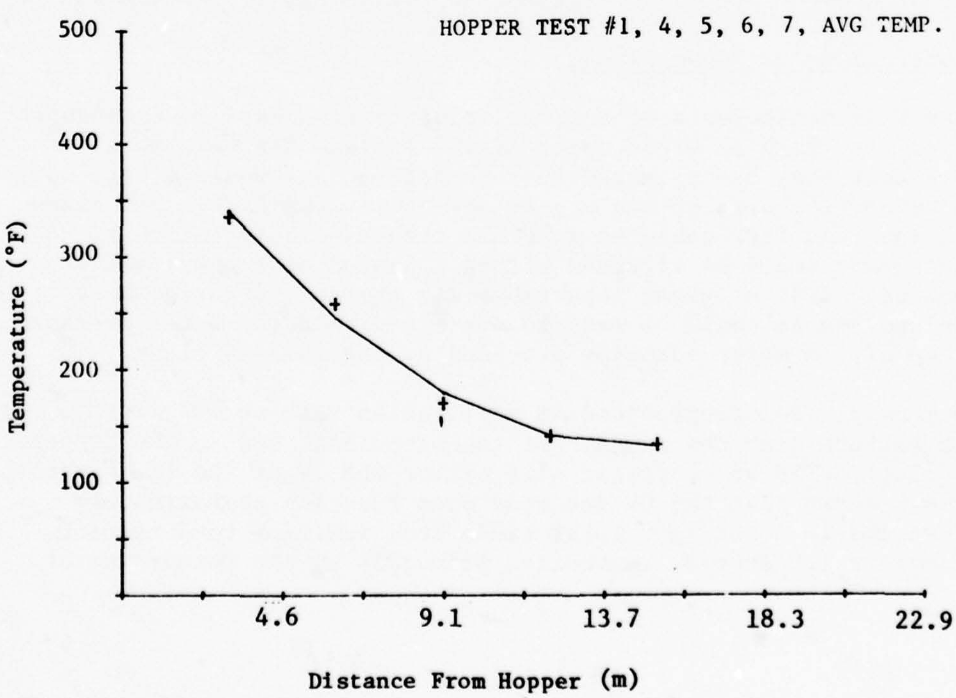


TABLE XII

Propellant Recovery Data For Hopper Tests

Test No.	Wet Weight (kg)	Dry Weight (kg)	Ratio W/D
2	136.9	123.4	1.12
4	82.56	78.0	1.05
6	49.9	39.9	1.25
7	49.9	39.5	1.26
8	103.4	92.5	1.11
9	78.9	68.0	1.16
10	139.3	122.5	1.13
11	129.3	115.7	1.11
12	119.7	109.3	1.09
13	86.6	73.0	1.18
14	88.0	75.3	1.16
15	95.3	86.6	1.09
16	91.2	77.6	1.17
17	128.8	97.1	1.32
18	206.8	180.5	1.14
		Average	1.156
		Std. Dev.	0.073

the bottom ignition and the top detection. The total time from ignition to water on the fire was shown to be approximately 1.5 seconds.

The results of the test firings also demonstrated that, should a fire occur in the hopper, there would be an eruption of the material caused by the gases generated at the outset of the fire. This eruption could be effectively controlled, first, by allowing it to vent through the roof, and second, by the rapid application of the water deluge to quench the fire, thus keeping the maximum temperatures and pressures in the surrounding environment at a minimum. As a result, it was shown that the fire could be effectively controlled and that there would be no damage to the hopper or the surrounding operating equipment and structural building.

Indiana Line Burn Tests

Discussion

The third phase of the program was to design, test, and evaluate a water deluge system to extinguish a fire in a long conveyor line which is moving single bags of propellant, one aligned behind the other, between the operations of the modernized bag loading process. Several of these conveyor lines are used in the LAP facility; the principal one of concern to this program was the conveyor which transported the loaded bags from the bagged loading operation station to the large accumulators where the bags were stored for subsequent assembly into the complete seven-bag M-67 charge. The safety problems posed by the single bag being conveyed down a lengthy conveyor were quite different from those of concern in the propellant receiving hoppers and the large accumulator bins. These unique problems were considered and an effective water deluge system was designed for the single bag, line burn conveyor problem.

On the conveyor system, the bags are never more than a single layer thick, although, in many cases these bags will be literally touching one to the other end to end. A fire could be ignited at any random point along the conveyor, consequently, quick extinguishment was most necessary to prevent propagation of the fire back to the bag loading operation or at the other end into the storage accumulators. In the LAP facility there are seven bag loading stations and seven accumulators, consequently, there are seven long conveyor lines transporting the bagged propellant between the stations. To satisfy the water adequacy constraint at the Indiana AAP, it was necessary to determine the minimum water application rate which would achieve a successful extinguishment of the fire should one occur.

To evaluate the effectiveness of the system, it was decided to conduct the tests under the worst case condition. All of the experimental test firings were carried out using the No. 1 bags (reference Table I) since these bags contained the more rapidly burning single perforated M-1 propellant, and also because these were the largest bags containing the most propellant. Figures 16 and 17 schematically show the placement of the No. 1 bags end to end, in the conveyor tray. Ignition of the fire was accomplished by inserting an Atlas electric match into the center bag of the 11 bag string.

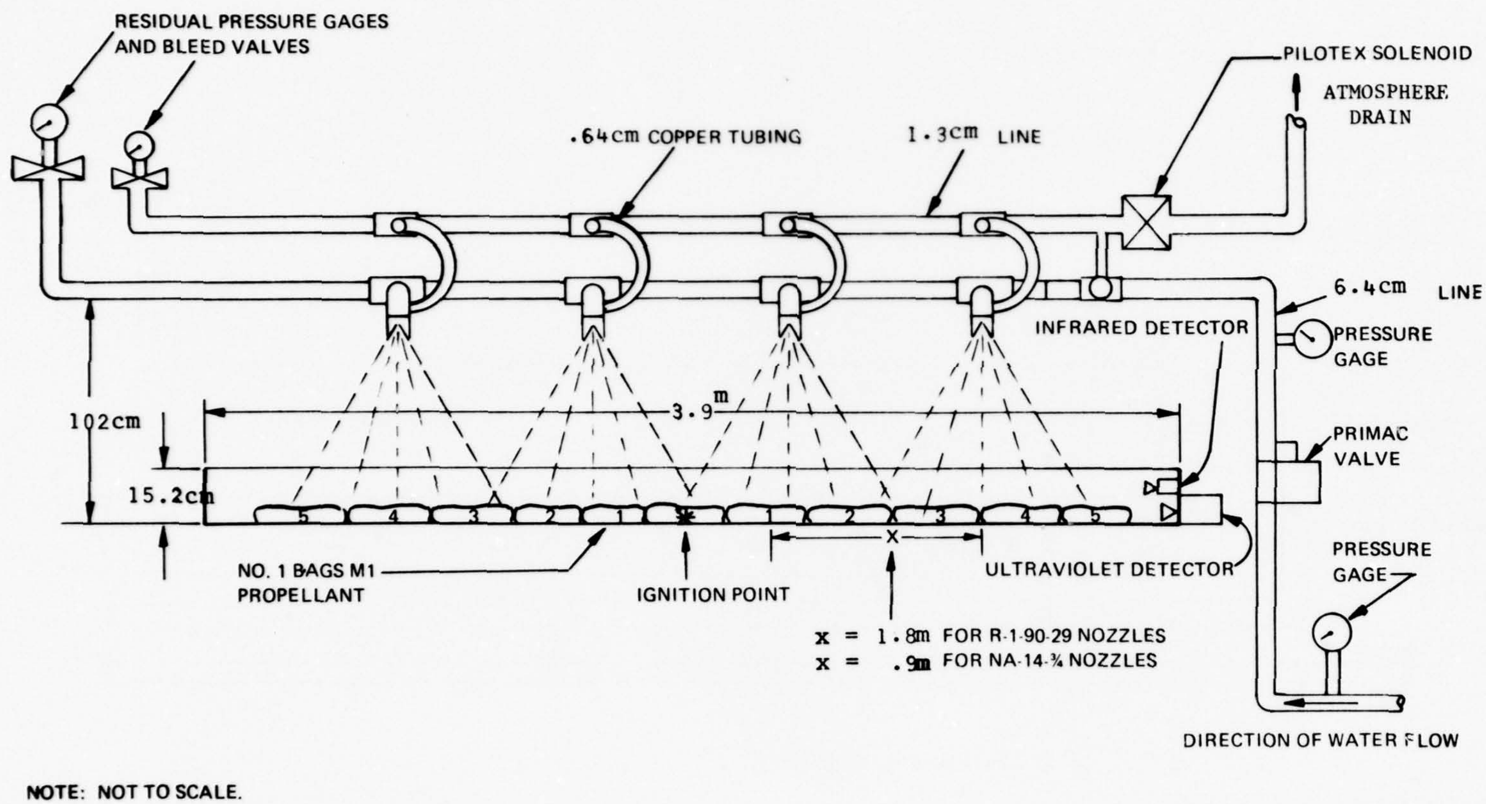
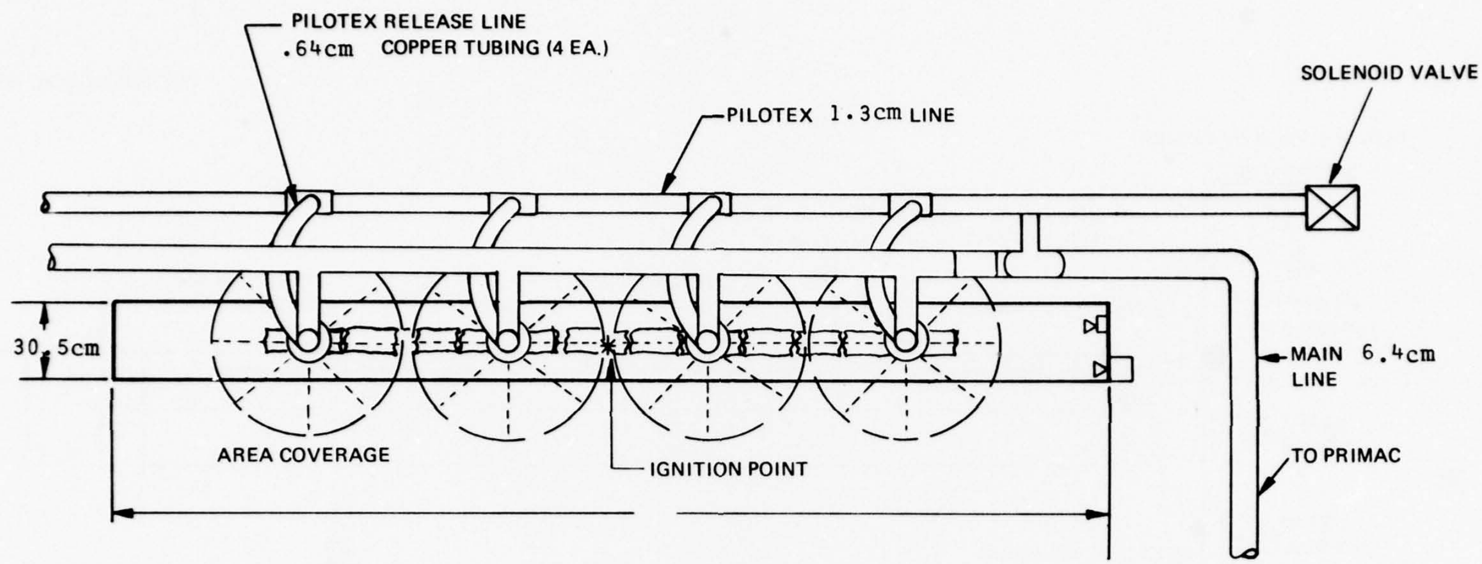


FIGURE 16. Composite Sketch Of Both Pilotex And Primac Deluge Systems Used On "Line Burn" Tests



NOTE: NOT TO SCALE.

FIGURE 17. Top View Of Line Burn Deluge Systems

Both the UV and IR detectors were used to sense the fire, and throughout the tests, an evaluation was made of the IR response times. The detector was mounted at one end of the conveyor to simulate the probable location of the fire sensor with respect to a 6.1 m distant ignition point in the plant situation.

Two water deluge systems were designed and tested for application against the line burn type of fire occurring in the bag conveyor system. These two deluge systems are shown schematically in Figures 16 and 17. Here a composite sketch was used to illustrate the two systems. The first was the now familiar Primac valve controlled water deluge system which utilized the R-1-90-29 nozzles placed at a height of 101.6 cm above the conveyor bed. Because of the conical pattern of the water emitted from the nozzle, this height of 101.6 cm controlled the water application rate, which will be discussed a bit later. The second water deluge system employed the use of the "Pilotex Deluge Sprinkler System." The Pilotex is a high speed system using pilot operated nozzles. Each of the many nozzles is normally in the closed position with a poppet valve in each nozzle being held against a discharge orifice by pressure within the poppet cylinder. When the pilot line pressure drops, the main line pressure overcomes the differential, forces the poppet up, thus opening the sprinkler orifice and very rapidly starting the full discharge from the nozzle.

To basically differentiate the differences between the Primac system and the Pilotex system, note that the Primac valve controls the release of the water pressure into the wet-line, and prior to release, the water is held in the nozzle by a blowoff plug or diaphragm at the face of the nozzle. In the Pilotex system, flow of the water is regulated by the poppet valve located in each of the nozzles. In the Pilotex system, a signal from the fire detectors activates and opens a solenoid valve which dumps the pilot line water pressure to the atmosphere. When pilot pressure is restored, the poppet recedes, even against the main fire line pressure. This latter statement is an extremely important point which can be easily accommodated, however, is worthy of special note. In a plant fire situation, there is the very real possibility that electric power in the building could be lost during the fire. Should this occur, the solenoid valve could close, thus, restoring the pilot pressure and shutting off the water deluge system. Obviously, a simple mechanical lockout system could and should be incorporated into the Pilotex system before its use in a manufacturing facility. Conversely with the Primac valve system discharged, the Primac valve will remain open until it is manually reset.

The comparative response times of these two deluge systems will be discussed in the next section of this report. It is sufficient to note at this point that the sequence timing of the events was conducted using the identical sequence timing network that was described in Section II and was used successfully for both the Hopper and Accumulator tests.

The intensity of the fires in the hoppers and accumulators was sufficient to cause concern over the possible rise in ambient pressures

or temperatures and the hazards that could result. In the line burn tests, however, it was realized very early in the program that the water deluge system was most effective in controlling the fire and limiting the burn to only a few bags. Consequently, no effort was made during the line burn experiments to monitor either pressure or temperature rise in the surrounding environment.

Because of the minimal burning which occurred in the line burn tests, recovery of the unburned bags and recording the test results was simple. In every test, a total of 11 bags was placed in the conveyor with ignition occurring in the center bag. This first bag was totally consumed in every test, and the remaining five bags on each side of center were counted in the recovery. To be counted as a recovered bag more than 95 percent had to be recovered. Slight singes and small burn spots were discounted. Hence a "total recovery" was judged to be 10 bags.

Results of the Line Burn Tests

The Indiana line burn tests consisted of 27 firings, 15 of which were made using the Primac valve water deluge system and 12 using the Pilotex valve system. The results of these tests are shown in Tables XIII and XIV. As was the case in the previously described hopper and accumulator evaluation, the first six shots shown in Table XIII were made as "preliminary" firings to evaluate the functioning of the deluge system using the Primac valve. During these tests several nozzles were tested at varying residual water pressures with only a marginal success, as noted by the number of bags recovered. Recall that a score of 10 bags recovered constitutes a perfect score. In tests 7 thru 15 a four nozzle deluge system was evaluated which employed the 90° spray nozzle at a residual water pressure of only 193 kPa. This pressure corresponds to a static line pressure of 241 kPa, much less than the 448 kPa allowed at the Indiana facility. These tests were performed specifically to determine the minimum water pressure and water coverage in LPM/m^2 which would effectively extinguish a line burn fire. Note that in the confirmatory shots 7 thru 15, the percentage of bags recovered was excellent.

To determine the MINIMUM WATER APPLICATION RATE a simple test fixture was built with which to measure the water distribution over a given "target" area. Tests were made using this fixture under a number of conditions in which the water pressures, the nozzles and the area coverage were varied. One of these test configurations duplicated the conditions which were used for the conduct of the "line burn" propellant burn tests.

The water distribution test fixture consisted of assembling 16, one-inch I.D. tubes, placed on 5 cm centers, thus capable of covering an area on a line 81.3 cm long. Tube No. 1 was placed directly under the nozzle, and the remaining tubes covered the area on a radius projecting from the center line. The quantity of water collected in each tube for a period of one minute was then measured and converted to a value for

TABLE XIII

Line Burn Tests Using
Primac Valve - UV Detector

Test No.	Deluge	Residual Water Press. (kPa) *	No. of Bags Recovered
1	4-50°	41	4
2	4-50°	69	0
3	4-50°	83	5
4	4-100°	41	2
5	4-50°	280	8
6	4-50°	280	9
7	4-90°	190	9
8	4-90°	190	9
9	4-90°	190	10
10	4-90°	190	9
11	4-90°	190	8
12	4-90°	190	8
13	4-90°	190	8
14	4-90°	190	7
15	4-90°	190	8

All tests used electric match ignition at or near midpoint.
All tests used eleven, #1 bags of M-1, SP placed end to end. Only full bags counted in recovery. Ten bags recovered is a perfect score since the #11 bag is the ignition bag and is lost in all cases.

* Average 44.8 LPM/m^2 (1.1 gpm/ft^2) depending on wind direction and position under nozzles.

TABLE XIV

Line Burn Tests Using
Pilotex Valve - UV Detector

Test No.	Residual Water Pressure (kPa)	No. of Bags Recovered
16	400	9
17	400	7
18	400	9
19	400	10
20	400	9
21	400	8
22	170	9
23	170	9
24	240	9
25	240	9
26	540	9
27	540	9

* 4-14NA-3/4 Nozzles every 7.6 cm at 101.6 cm Hgt.

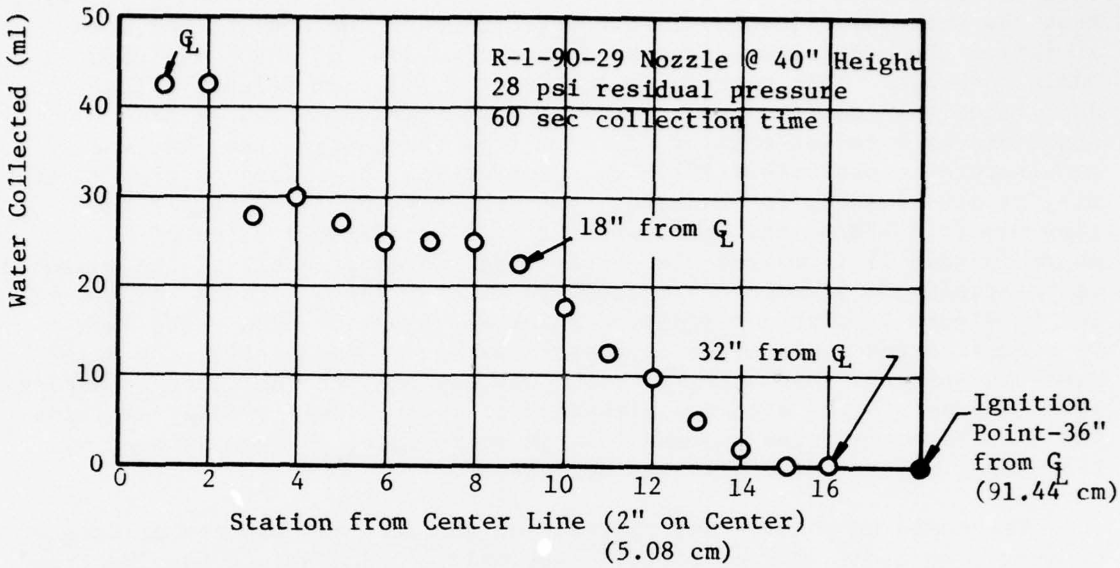
Average Water Application: 170 kPa (25 psig) yields 105 LPM/m^2 (2.6 GPM/ft^2)
240 kPa (35 psig) yields 73.3 LPM/m^2 (1.8 GPM/ft^2)
400 kPa (58 psig) yields 65.2 LPM/m^2 (2.4 GPM/ft^2)
540 kPa (78 psig) yields 126.3 LPM/m^2 (3.1 GPM/ft^2)

both the flow rate and the water coverage over that given area. These data are presented in the graph of Figure 18, and it can readily be seen that the water distribution is not uniform under the nozzle, nor does it follow the manufacturer's stated specifications of a 90° included angle coverage. This particular nozzle at a 101.6 cm height, which duplicated the conditions for the line burn tests, covered an area described by a radius equal to 71.1 cm from the center line, not the manufacturer's prescribed 101.6 cm. Converting these data to area coverage, it can be seen, for example, that directly under the nozzle the flow was 73.3 LPM/m^2 and this coverage trailed off to a value of 0 approximately 71.1 cm from the center line. Averaging all of the measured values yields an area coverage equal to 44.8 LPM/m^2. Note on the graph and in Figure 16 that our ignition point for the line burn tests was 91.4 cm from the center line of these nozzles. Consequently, the only water coverage at that specific point was due only to the water splashing over, and not to the direct application of water. This readily explains why the center ignition bag was lost in every case, whereas in most of the tests, all of the other bags were saved.

It should be pointed out that in our earlier measurements of water coverage, we used a larger catch bucket and recorded values ranging from 20.4 to 122.2 LPM/m^2 and reported an average value of 44.8 LPM/m^2 in Table XIV. These values can be compared to the calculated values, using the manufacturer's specifications, which range from 29.3 to 57.0 LPM/m^2 depending on which value one uses for the included angle prescribed by the nozzle.

To summarize this discussion, we know that we were able to extinguish the fires within the first or second bag from the point of ignition. We also know that we were able to extinguish the fire in all cases at a point 24 inches (station 12 in Figure 18) from the center line of the nozzle. The water coverage at that point is less than 20.4 LPM/m^2. After careful review of these data, it would appear that a properly designed deluge system for in-plant use could be based on a requirement of 20.4 LPM/m^2 and yet be fully capable of extinguishing fires that might occur in a line conveyor.

After converting the water deluge system from the Primac valve to the Pilotex valve deluge, tests 16 thru 27 (Table XIV) were conducted at varying residual water pressures. In the Pilotex system, four nozzles were used, spaced three feet apart and placed at a height of 101.6 cm over the propellant bed. This placement of the nozzles approximated the same area coverage as was obtained with the Primac system, although the test results showed that the number of bags recovered was relatively insensitive to the rate of water application. Qualitatively reviewing the test results of both water deluge systems, it was apparent that the most important design parameter was to achieve a uniform coverage over the entire propellant bed. Since the bags were only one layer deep, the area coverage system worked very well, and there was no need for a cut-off type (high pressure) nozzle that had been used in the accumulator



40 ml = 73.3 LPM/m^2 (1.8 GPM/ft^2)

28 ml = 52.9 LPM/m^2 (1.3 GPM/ft^2)

Avg. 14 stations =

22.5 ml = 44.8 LPM/m^2 (1.1 GPM/ft^2)

FIGURE 18. Water Distribution For Line Burn Tests

* See me-ric conversion chart

TABLE XV

Comparison Of Primac And Pilotex Valves

	IGN.-UV (Sec)	I-Valve (Sec)	I-WO (Sec)	UV-WO (Sec)	I-EXT. (Sec)	AVG BAG REC.
Using Primac Valve	0.75	0.90	1.11	0.36	7	8.4
Using Pilotex Valve	0.84	0.89	1.03	0.19	7	8.8

Notes: Time from UV to Water-on appears to favor the Pilotex. This margin is also reflected in the number of bags recovered.

tests. Also, since the ignition of the fire could be readily seen by the detectors, the fire did not have much chance to propagate before the activation of the water deluge system. This fact is borne out by a review of the time response data for the two systems, as shown in Table XV. Here it can be seen that the time from UV detection to water-on was 0.19 sec for the Pilotex and 0.36 sec for the Primac, thus favoring the Pilotex system. The average number of bags recovered also slightly favors the use of the Pilotex.

Conclusions From Indiana Line Burn Tests

In summary of the Line Burn Tests it can be concluded that a water deluge fire extinguishing system is most effective. In almost all cases the fire was limited to the single ignition bag, with only slight and occasional spread to adjacent bags. The fire can be readily sensed and water applied directly over the full conveyor bed in approximately one second. The data indicate that the Pilotex valve system is slightly better than the Primac valve, however to justify this conclusion, more tests in a controlled environment (not outdoors) and with a carefully engineered nozzle system should be carried out. Also, the comparative evaluation should include consideration of the Pilotex solenoid shut-off provision and the additional cost of the Pilotex pilot line.

IV. SUMMARY AND CONCLUSIONS TO ALL TESTS

The full-scale tests of a water deluge system to extinguish M-1 propellant fires such as might occur at the Indiana AAP were most successful. The test program demonstrated that there are several fire detectors, commercially available, which can sense the propellant fires, quickly actuate a water release valve, and apply water to the source of the fire. Three different water deluge systems were designed and tested and were shown to be most effective in quenching fires as might occur in the propellant receiving hoppers, the bagged propellant accumulators and the line conveyors which transport the bagged M-1 propellant. Each of these deluge systems were custom designed to provide uniform area coverage over the fire source and to provide water coverage uniquely designed to attack each type of in-plant operating condition.

All of the tests were conducted in full-scale and, to simulate the in-plant operating conditions, constraints were placed on the tests to duplicate as closely as possible the worst case conditions. These constraints included bottom ignition of the propellant such that the fire had to transcend through the propellant bed depth to the top surface at which point the detectors were permitted to view the fire. Each of the water deluge systems was designed with the constraints of water adequacy and water flow rate which are available at the Indiana AAP. Also, the tests were designed such that they simulated, at least in part, the in-plant environment with regard to the proximity of building walls, roof, reflecting surfaces, and other structural impediments to the application of water on the fire sources.

During the conduct of each test, the time of occurrence of each event was monitored both electronically as well as by high speed film coverage. Table XVI presents a summary of the timing data for each of the three test series, i.e., the accumulators, the hoppers, and the line burn tests. These data, in summary, present the time from ignition to the detection by either the IR or UV detector, the time required for functioning of the Primac water release valve, and the time required to apply water on the fire source. Lastly, the mean time from ignition to complete extinguishment is given. It is important to pause and examine these data carefully. Column 1 of Table XVI indicates that it required approximately one full second from the time of ignition to the first detection by a UV sensor. These times, of course, varied depending on the thickness of the propellant bed, with the detection of a line burn fire requiring much less time than for detection of an accumulator which must burn through approximately 40.6 cm of propellant before it can be sensed by the detector. Comparing the UV response to the IR response, one sees that the IR is approximately 50 msec slower in response. For most of the tests, the Primac valve was set to function on a signal from either the UV or IR detectors. Since the UV detectors responded first, the mean time from detection to actuation of the Primac valve was 50 msec, and from actuation of the valve to water on the fire required 200 msec. The total time from ignition to full extinguishment is seen in column 6 to range from seven seconds for the simple line burn tests to as long as 43 seconds for the extinguishment of the fire in the large accumulator containing bagged M-1 propellant.

Accumulator Fires - The principle of using cut-off deluge nozzles to penetrate through the 40.6 cm depth of bagged propellant was demonstrated to be most effective in attacking this type of fire. The deluge operated on a maximum of 448 kPa static water pressure at a flow rate of 472.6 LPM/m^2 from the deluge nozzles and 101.8 LPM/m^2 from the area coverage nozzles. The test clearly demonstrated that the fire can be extinguished within 2.44 m of the point of ignition, regardless of where the fire occurs along a 21.3 m accumulator.

The tests also demonstrated that, because of the rapid extinguishing of the donor accumulator fire, there was only a relatively small rise in the ambient temperature surrounding the accumulator. These effects were insufficient to cause any significant damage to the accumulator room at the Indiana AAP. Lastly, and no doubt most important, should a fire occur in the accumulator room at the Indiana AAP, it can be considered as a Class 1.3 hazard rather than a possible Class 1.1 hazard.

Hopper Fires - The full-scale tests of the deluge system to extinguish large hopper fires were also most successful in that it was demonstrated that the deluge system operating at 407.4 LPM/m^2 of coverage can control and eventually extinguish these fires before any catastrophic damage would occur to either the hopper or to the surrounding facility. Testing under the worst case condition of bottom ignition, top detection and a maximum of 448 kPa water pressure, the fires could be contained and extinguished before a significant rise in temperature or ambient pressure occurred. Also of significance is the fact that a fire in a large receiving hopper can be effectively controlled and treated as a Class 1.3 hazard rather than as a Class 1.1 explosive hazard.

Line Burn Fires - Although fires on a line conveyor are small and easily controlled, the test program clearly demonstrated that these fires can be rapidly extinguished using a minimum of water from the critical supply at the Indiana AAP. These tests also provided a comparison between the Primac valve deluge system and the Pilotex deluge system, with the result that either system is equally effective in quickly releasing water to the fire source. The selection of either system for installation in a propellant manufacturing facility would, therefore, depend largely on other considerations related to the installation complexities and costs involved.

TABLE XVI

Summary Of Timing Data For Accumulator
Hopper and Line Burn Tests

	I-UV	I-IR	I - Primac		I - Water/On		UV-Water/On	Ignition to Extinguishment
	Scope	Scope	Film	Scope	Film	Scope	Scope	
Accumulator (Avg.)	1.246	1.298	1.354	1.288	1.63	1.527	0.281	43.12
Hopper (Avg.)	1.096	1.156	1.19	1.152	1.531	1.532	0.436	17.33
Line Burn-Primac	0.75	Not Used	--	0.90	--	1.11	0.360	7.0
Line Burn-Pilotex	0.84	Not Used	--	0.89	--	1.03	0.187	7.1

RECOMMENDATIONS

1. Storage of bagged M-1 propellant randomly stacked to a height of 40.6 cm in a 21.3 m accumulator is recommended as a Class 1.3 hazard when the accumulators are protected with a cut-off and area coverage nozzle deluge system that delivers water at a rate of 472 and 101.8 LPM/m^2, respectively.

2. Fires occurring in an M-1 propellant receiving hopper at bed depths in excess of 82 cm can be treated as a Class 1.3 hazard when 407 LPM/m^2 of water coverage is provided by a cut-off nozzle deluge system.

3. An ultra-violet detection (U.V.) system is recommended to sense M-1 propellant fires that can occur in accumulators or hoppers at the Army Munition Plants.

4. Information derived from these water deluge tests should be incorporated into the TM-5-821-1 Fire Prevention Manual.

APPENDIX A

Hazard Analysis Of Pressure Rise

APPENDIX A
HAZARD ANALYSIS OF PRESSURE RISE

An important part of the research program was the analytical effort to study the pressure buildup as a result of burning large quantities of M-1 propellant and how this pressure buildup would be affected, should it be confined in a sealed conveyor in one case, or should it be confined in a relatively sealed room in another case. It is obvious that in any accidental propellant fire, some quantity of propellant will be burned before the detector can sense the fire and activate a water deluge system to extinguish that fire. The question then is asked, "How much propellant can one tolerate to be burned before secondary catastrophic events could occur, i.e., the rupture of a sealed conveyor, the possible blowoff of a frangible roof of the building, or the possible collapse of the building walls as a result of an internal pressure?" SwRI took several approaches to this descriptive analysis and these will be discussed.

Of interest was the peak static pressure that could develop in a large plenum due to the accidental burning of a large quantity of propellant. The "plenums" of interest to this study were the rooms at the Indiana AAP which house the loose propellant receiving hoppers, and the seven large accumulators holding the bagged propellant. The concern over the receiving hopper rooms was readily discounted following a review of the structural drawings and the placement of the hoppers under a vented roof (see Figure 10, p. 38). This study was reinforced after reviewing the test results, wherein it was demonstrated that: 1) No explosion occurred; 2) The hoppers did not rupture or bulge; and 3) All of the burning propellant and expanding gases would vent directly through the roof and pose no further hazard.

The accumulator room at Indiana, however, was a serious consideration. The test data proved that a fire in an accumulator could be controlled and extinguished within 2.44 m of the point of ignition. Also, it was shown that propagation to adjacent accumulators could be prevented; however on the negative side it was shown that approximately 226.8 kg M-1 would burn before extinguishment could be completed. Quick reference to the Handbook* revealed that M-1 propellant produces 858 ml/gm of gas when burned completely and after the gas has cooled to ambient temperature. This value can be increased by an order of magnitude if the gas is still contained within the "fireball" of still burning propellant at a temperature in excess of 2400°K. Hence, 226.8 kg of M-1 will yield 1982 m^3 of gas.

More realistically, consider the test observations. This quantity of 226.8 kg created a fireball in open air testing which rose 15.2 m into the air and the total time to burn was approximately 43 sec. (see Tables IV and V, pp. 28 and 29). This time-to-burn allows for the venting

*Properties of Explosives of Military Interest, AMCP 706-177, Engineering Design Handbook, Explosives Series, March 1967.

of gases from a room thus partially alleviating some of the pressure rise and resultant overpressure hazards. Unfortunately however, the tests indicated that the fireball would totally engulf the Indiana accumulator room.

Consider now the structural design of the room housing the seven long accumulators. Basically, the walls are reinforced concrete block and the roof of the high-bay over the accumulators is made of blow-out panels designed to fail at (20 psf) 97.7 kg/m^2. (For comparison, a 50 mph wind load $\approx$ 6 psf and 7.6 cm snow load $\approx$ 16 psf.) For economic reasons, the failure of only the roof due to a fire-caused overpressure, could be a most costly, if not hazardous occurrence.

To examine this problem, SwRI referred to the Filler* method of calculating the peak static pressure resulting from the generation of a gas in a closed vessel (room). This method can be used when the gases generated are a small percentage of the gases in the vessel at the time of occurrence.

Filler derived the relationship

$$P = \frac{H(r-1)}{V}$$

where

P = pressure rise

H = heat added to the gas

r = ratio of specific heats Cp/Cv

V = volume of the room

Using the specific heat ratio of 1.4 for air, the pressures being considered and conversion factors, this equation can be expressed as:

$$P = \frac{3844\ Wh}{V}$$

where

P = pressure rise in psi

W = weight of propellant in lbs

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* Wm S. Filler, "Past Detonation Pressure & Thermal Studies of Solid High Explosives in a Closed Chamber", NAVORD Reports 2934 and 3890, Sixth Symposium on Combustion, Reinhold Publishers, Inc., N.Y. pp. 648-657.

h = heat of combustion in k cal/gr

V = volume in ft^3

The accumulator room at the Indiana AAP measures 19.2m x 8.5m x 7.0m high with an open adjacent room measuring 5.11m x 8.5m x 3.96m high for a total volume of 46,669 cu. ft. Assuming that this is a sealed room (no venting), there are no radiation losses and no water deluge systems, how much propellant can be burned without exceeding the 20 psf (0.139 psi) internal pressure limit before frangible roof failure? Heat of combustion of M-1 propellant is 2.975 k cal/gr*

$$W = \frac{PV}{3844\ h}$$

$$= \frac{0.139 \times 46669}{3844 \times 2.975}$$

$$= 0.567 \text{ lbs} \quad (257.2 \text{ gms})$$

Therefore, should only about 0.6 lbs of M-1 burn in the accumulator room, some failure of the roof could occur. Conversely, should the test result 500 lbs burn before extinguishment, again without venting, the pressure in the room could rise to:

$$P = \frac{3844 \times 500 \times 2.975}{46669}$$

$$P = 122 \text{ psi } (17{,}600 \text{ psf})$$

Consider however a more realistic case, i.e., total burn time of 43 seconds (reference pp. 28 and 29) with adequate roof venting of the room. From the test results:

$$\frac{500 \text{ lbs of M-1}}{43 \text{ seconds}} = 11.63 \text{ lbs/sec. burned} \times 140 \text{ cu ft/lb}$$

$$= 1628 \text{ ft}^3\text{/sec} \quad (46.1 \text{ m}^3\text{/sec})$$

of gas will be generated.

At the Indiana AAP the large accumulator room has approximately 50 percent venting in the 63 ft. x 28 ft. room; thus 882 sq. ft. of vent area. Using the values:

---

* "Military Explosives," TM-9-1910

A_v = vent area = 882 ft^2

ρ_{air} = density of air = 0.0766 lb/ft^3

C_D = drag coefficient = 0.8

g = gravity = $32.2 \dfrac{lb_m ft}{lb_f sec^2}$

in the relationship*

$$\Delta P = \left(\frac{Q}{A_v C_D}\right)^2 \left(\frac{\rho}{2g}\right)$$

$$= \left(\frac{1628}{882 \times 0.8}\right)^2 \left(\frac{0.0766}{2 \times 32.2}\right)$$

$$= 5.323 \times 1.189 \times 10^{-3}$$

$$= 6.33 \times 10^{-3} psf$$

$$= 4.3 \times 10^{-5} psi$$

This pressure rise is negligible for the full vented roof. Two other calculations are of interest:

1) Assume: 500 lbs burn before water extinguishment

Question: How much simple vent area (doors, etc.) is required to prevent roof failure at 20 psf?

$$20 \text{ psf} = \frac{1628}{A_v \times 0.8}^2 \quad \frac{0.0766}{2 \times 32.2}$$

Answer: A_v = 15.7 sq. ft. (1.46 sq m)

This is approximately equal to one open door.

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* "Basic Mechanics of Fluids" by H. Rouse and J. W. Howe.

2) Assume: No water deluge and entire accumulator room burns (4000 lbs x 7 accumulators = 28,000 lbs) in 2 minutes.

Question: What will be the peak pressure with 50 percent roof venting?

$$\frac{28{,}000 \text{ lbs}}{120 \text{ secs}} \times 140 \text{ ft}^3/\text{lb} = 32{,}666 \text{ ft}^3/\text{sec of gas generation}$$

and: $$\Delta P = {\frac{32666}{882 \times 0.8}}^2 \quad \frac{0.0766}{2 \times 32.2}$$

Answer: $\Delta P = 2.55$ psf

APPENDIX B

Comparative Evaluation Of Fire Detectors

APPENDIX B
COMPARATIVE EVALUATION OF FIRE DETECTORS

In order for a deluge system to extinguish a fire on a processing line in an explosives or propellant handling facility, the system must have a sensor which will detect the fire and a control system which will activate a water valve within milliseconds of the fire appearing in the view of the detector. The detector cannot normally be located physically near the most probable point where fire could occur. Therefore the sensor must be capable of detecting a fire at a distance of up to 6.1 m. Usually there is some solvent, including water, present during the handling processes, or dust is created, or the fire may be obscured by smoke. The sensor must be able to detect a fire through such atmospheres. Finally the sensor must not give false alarms, as for example when sunlight or incandescent or fluorescent lights suddenly appear in the view of the sensor. Such false alarms would result in stoppage of the processing line and in undue loss of the explosive being processed. The potential sources of the fire are the explosives or propellants being processed, both low and high explosives, the solvents being used in the processes and other combustible materials which could be present.

To detect and cause a reaction to a fire, there are a variety of detectors available with a wide variation in spectral response and time of reaction. As an adjunct to the major program SwRI made a cursory survey of these available detectors and elected to evaluate three candidates.

The three detector systems evaluated are ones which have been selected for use in explosives handling facilities or were selected as a result of earlier programs. All three of the detector systems react to electromagnetic radiations emitted by the fire, or, in short, the flames, visible or invisible. These radiation sensitive detectors have the capability of sensing fire remotely and quickly, which the more commonly-encountered household or industrial sensor systems do not. All three of these detector systems use, or can use, a relay to operate the water valve. Each of these detector systems uses a different band of radiation wave lengths in its operation as follows:

- Ultraviolet - Detronics, Inc., 1850-2450 Å
- Infrared - ADT Corp., 7000-28,000 Å
- Visible - Pyrotector 4000-8500 Å

The purpose of the program was to measure the reaction time of each of the three detectors responding to identical flame sources, and their abilities to activate a Primac water deluge valve.

A test matrix was established to monitor the detector response at four different distances, and to monitor what effect three different dust, solvent, water, and smoke concentrations will have upon the detector ability

to sense a fire. Hence, this test matrix would encompass $4 \times 3^4 = 324$ tests for each fire source. A total of seven fire sources were selected for evaluation, and these were selected to be representative of either propellants, high explosives or their commonly used solvents such as ethyl alcohol and ether. Thus, the total matrix encompassed 324 tests for each of seven sources for a total of 2268 shots. For redundancy, this number of tests could be multiplied by a factor of two or three shots each, depending upon the statistical reliability one might be interested in. The total number of tests, therefore, constitutes what might be considered an unreasonable number of tests. Consequently, SwRI has approached the evaluation of the test matrix using a statistical technique commonly known as "Fractional Factorial Analysis".* The results of this statistical analysis led to the establishment of the test matrix shown in Table XVII which will be discussed in detail later.

The test program used the experimental setup as shown in Figure 19 . Within the test chamber a fire was started at one end and the radiation was shielded from the detectors by a window which, when opened, would expose the flame source to the detectors which were mounted at the far end of the conveyor. The distance between the flame source and the detectors was varied, as was the ambient atmosphere between flame and detectors. As shown in the schematic drawing, the signal from each of the three detectors was transmitted back through an amplifier, a switch and a relay and the response of the detectors was displayed on an oscilloscope. The output signal from the relay was used to trigger a flashbulb which was indicative that a signal had been sent to a Primac water deluge valve. Each of the three oscilloscope traces were started when the window was opened. Hence, the response time of each detector was recorded and the comparative response times between the three detectors was similarly displayed on the same oscilloscope record. The response of each of the detectors, as a function of the variables within the test matrix are reported.

Displayed in Table XVIIare the response times for the three detectors when they were exposed to seven different fire sources. In column 2 of Table XVII, it can be seen that each flame source was placed at a distance of 3.7, 2.7, 1.8 or .09 m from the detectors, and the remaining columns of the table display the response times through atmospheres of air, black powder smoke, dust, acetone, water in the form of steam, water in the form of mist, ethyl alcohol and ether. Reading the table, one immediately recognizes that M-1 propellant fire was not seen by several detectors through a black powder smoke. Reading across the M-1 propellant column, one can see that most of the detectors could see through an acetone vapor atmosphere and similarly through a water, ethyl alcohol and ether atmosphere.

Still referring to Table XVII, and reading down the first column, the data indicate that with an ethyl alcohol fire source, for the most part,

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* Owen L. Davies, "Design and Analysis of Industrial Experiments," Hafner Pub. Co., 1967.

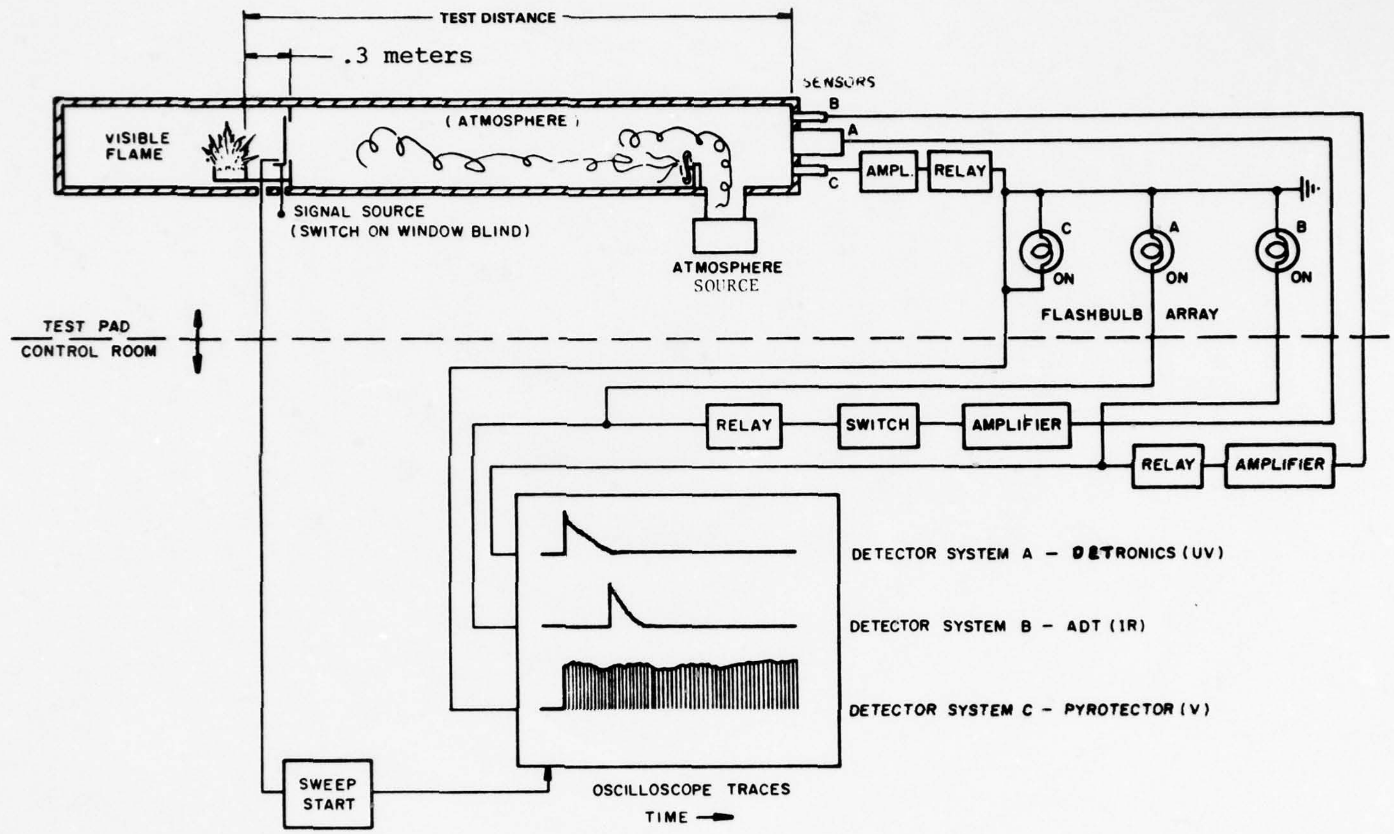

FIGURE 19. Schematic Of Detector Evaluation Test Chamber

TABLE XVII

MEAN RESPONSE TIME OF EACH DETECTOR FOR VARYI
DISTANCE AND ATMOSPHERE

To Detect Fire of	At Distance	Air N	Air UV	Air IR	Air V	Black Powder Smoke N	Black Powder Smoke UV	Black Powder Smoke IR	Black Powder Smoke V	Dust (AC Fine) N	Dust (AC Fine) UV	Dust (AC Fine) IR	Dust (AC Fine) V	Acetone N	Acetone UV	Acetone IR
M1 Propellant	3.6m	8/5	.08	.29	.24	1	.12	NR	NR	1	NR	NR	NR	3	.15	.84/NR
	2.7m	2	.08	.21	.22	2	.06/NR	.12/NR	.10/NR	1	.23	NR	.50	1	.12	NR
	1.8m	1	.05	.08	.07	1	NR	NR	NR	4/3	.10/NR	.31/NR	.14/NR	1	.04	.09
	.9m	1	.02	.05	.05	1	.09	.24	.10	1/0	.08	.06	-			
WC 870	3.6m	2/1	.15	NR	.25	1	NR	NR	NR	1	NR	NR	NR	1	.10	NR
	2.7m	4/3	.07	1.46/NR	.07	1	NR	NR	NR	2	.10	NR	.18	1	.10	NR
	1.8m	1	.04	.20	.03	1	.22	NR	.10	1/0	NR	NR	-	1	.06	.20
	.9m	1	.04	.08	.03				.03	1/0	.16	NR	-			
Ethyl Alcohol	3.6m	2/1	.22	NR	NR									1	1.47	NR
	2.7m	2/1	.15	NR	NR					1	NR	NR	NR	1	.25	NR
	1.8m	2/1	.08	NR	NR	1	NR	NR	NR					1	.07	NR
	.9m	2/1	.05	NR	NR	1	NR	NR	NR	2/0	1.14	NR	-	1	.05	NR
Ether	3.6m	2/1	.14	NR	NR									1	.69	NR
	2.7m	2/1	.08	NR	NR					1	3.77	NR	NR	1	.12	NR
	1.8m	2/1	.05	1.36/NR	NR									1	.07	NR
	.9m	2/1	.04	.23	NR	1	.07	2.59	NR	1/0	.36	NR	-	1	.05	.10
Composition B	3.6m	3	.10	.34/NR	2.25	1/0	NR	NR	-					1	1.08	NR
	2.7m	2	.17	.48	8.94/NR					2	NR	NR	NR	4	.58	NR
	1.8m	1	.10	.24	.83					1/0	NR	NR	-	1	.05	.25
	.9m	1	.03	.03	.04	1/0	.18	NR	-	1/0	.15	1.38	-			
Composition C4	3.6m	1	.18	NR	NR	1/0	NR	NR	-					1	.54	NR
	2.7m	1	.11	NR	NR					2	.72	NR	NR	1	.13	NR
	1.8m	1	.05	NR	NR									1	.05	NR
	.9m	3	.03	NR	NR	1/0	NR	NR	-	1/0	.20	NR	-	1	.01	NR
Black Powder	3.6m	2/1	NR	.06	.04	1	NR	NR	NR	1	NR	NR	NR	1	NR	NR
	2.7m	2/1	NR	.05	.04					1	NR	NR	.07	2	NR	NR
	1.8m	1	NR	.06	.05	1	NR	NR	NR					1	NR	.10
	.9m	1	.16	.07	.06	1	NR	.08	.06	1/0	NR	.11	-	1	.10	.10

Note: The sample size N, is given for all sets of data. In several of the tests, data were obtained from the UV and IR detectors only; therefore, when two values of N are given, the value to the left of the slash is for the UV and IR detectors and the value to the right for the V detector.

2

TABLE XVII

EAN RESPONSE TIME OF EACH DETECTOR FOR VARYING FLAME SOURCE, DISTANCE AND ATMOSPHERE

	Dust (AC Fine)			Acetone				Water (Steam)				Water (Mist)				Ethyl Alcohol				Ether			
N	UV	IR	V	N	UV	IR	V	N	UV	IR	V	N	UV	IR	V	N	UV	IR	V	N	UV	IR	V
1	NR	NR	NR	3	.15	.84/NR	.23	2/1	.06	18/NR	.17	1	.08	.79	.32	2	.07	.61/NR	.19	1	.12	NR	NR
1	.23	NR	.50	1	.12	NR	.19	2	.06	.43	.43					2	.06	.35	.14	2	.04	.23	.20
/3	.10/NR	.31/NR	.14/NR	1	.04	.09	.09	1	.24	.55	.51	1	.06	.19	.18	1	.03	.29	.06				
/0	.08	.06	-																				
1	NR	NR	NR	1	.10	NR	.10	2/1	.07	NR	.07	1	.07	NR	.09	1/0	.05	NR	-	1	.05	NR	.09
2	.10	NR	.18	1	.10	NR	.07	2/1	.05	NR	.05	1	.07	NR	.06	1	.05	NR	.05	1	.05	.36	.05
/0	NR	NR	-	1	.06	.20	.07	1	.06	NR	.05	1	.06	.39	.07	1	.04	.37	.04	1	.03	.11	.03
/0	.16	NR	-																				
				1	1.47	NR	NR	2/1	.32	NR	NR	1	.27	NR	NR	1	1.09	NR	NR	1	.34	NR	NR
1	NR	NR	NR	1	.25	NR	NR	1	.10	NR	NR	1	.14	NR	NR	1	.36	NR	NR	1	.17	NR	NR
				1	.07	NR	NR	1	.06	NR	NR	1	.07	NR	NR	1	.07	NR	NR	1	.07	NR	NR
/0	1.14	NR	-	1	.05	NR	NR	2	.06	NR	NR	1	.04	NR	NR	1	.05	NR	NR	1	.05	NR	NR
				1	.69	NR	NR	2/1	.12	NR	NR	1	.16	NR	NR	1	.20	NR	NR	1	.10	NR	NR
1	3.77	NR	NR	1	.12	NR	NR	2	.09	NR	NR	1	.18	NR	NR	1	.07	NR	NR	1	.09	NR	NR
				1	.07	NR	NR	2	.09/NR	NR	NR	1	.07	1.97	1.20	1	.07	NR	NR	1	.05	NR	NR
/0	.36	NR	-	1	.05	.10	.22	1	.05	1.51	NR					1	.05	.37	2.22	1	.05	1.11	NR
				1	1.08	NR	NR	1	.20	NR	NR	1	.15	NR	NR	2	.28	.50/NR	2.24	1	.20	NR	NR
2	NR	NR	NR	4	.58	NR	.57/NR	1	.05	.32	.07	1	.05	.17	.10	2	[illegible]	.27/NR	.28/NR	2	.13	.32/NR	3.10
/0	NR	NR	-	1	.05	.25	.74					1	.05	.12	.12	2	.11	.11/NR	1.03	1	.15	.20	.34
/0	.15	1.38	-													1	.10	.79	2.36				
				1	.54	NR	NR	1	.22	NR	NR	1	.12	NR	NR	1	.15	NR	NR	1	.12	NR	NR
2	.72	NR	NR	1	.13	NR	NR	1	.05	NR	NR	1	.04	NR	NR	2	[illegible]	NR	NR	1	.07	NR	NR
				1	.05	NR	NR	1	.05	NR	NR	1	.05	NR	NR	1	.05	NR	NR	1	.05	NR	NR
/0	.20	NR	-	1	.01	NR	3.19	1	.05	NR	NR	1	.03	NR	NR	1	.03	NR	NR	2	.04	NR	NR
1	NR	NR	NR	1	NR	NR	.10	1	NR	NR	.13	1	NR	.10	.07	2/1	NR	.08	.05	2/1	NR	.09	.07
1	NR	NR	.07	2	NR	NR	.10	1/0	NR	.06	-	1	NR	.10	.07	1/0	NR			1/0	NR	.06	-
				1	NR	.10	.10	1/0	NR	.06	-	2	NR	.06	.05	1/0	NR			1/0	NR	.05	-
/0	NR	.11	-	1	.10	.10	.10	1	.09	.06	.04	1	.07	.05	.04	1	.11	.06	.05	1	.08	.05	.04

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TABLE XVIII

Summary of Sensor Response Data for Seven Fire Sources, Four Distances and Eight Atmosphere Contaminants

To Detect Fire Of	At Distance (m)	Response Time of Best (sec)	Response Time Multiple of Sensors ($Time_{Best}/Time_{Best}$)			Increase of Response Time of Best Caused By Atmosphere ($Response\ Time_{Atmosphere/Best}/Response\ Time_{Air/Best}$)						
			UV	IR	V	Black Powder Smoke	Dust	Water (Steam)	Water (Mist)	Ethyl Alcohol	Ether	Acetone
M1 Propellant	3.6	.08	1	3.6	3.0	1.5	∞	1	1	1	1.5	1.9
	2.7	.08	1	2.6	2.8	1 → ∞	2.9	1		1	1	1.5
	1.8	.05	1	1.6	1.4	∞	2 → ∞	4.8	1.2	1		1
	.9	.02	1	2.5	2.5	4.5	4					
WC 870	3.6	.15	1	NO	1.7	∞	∞	1	1	1	1	1
	2.7	.07	1	NO	1	∞	1.4	1	1	1	5.1	1.4
	1.8	.03	1.3	6.7	1	3.3	∞	1.5	2.3	1.3	1	1.5
	.9	.03	1.3	2.7	1	1	4					
Ethyl Alcohol	3.6	.22	1	NO	NO			1.5	1.2	5.0	1.5	6.7
	2.7	.15	1	NO	NO		∞	1	1.1	2.4	1.1	1.7
	1.8	.08	1	NO	NO	∞		1	1	1	1	1
	.9	.05	1	NO	NO	∞	22.8	1.2	1	1	1	1
Ether	3.6	.14	1	NO	NO			1	1.1	1.4	1	4.9
	2.7	.08	1	NO	NO		47.1	1.1	2.3	1	1.1	1.5
	1.8	.05	1	NO	NO			1.8 → ∞	1.4	1.4	1	1.4
	.9	.04	1	5.8	NO	1.8	9	1.3		1.3	1.3	1.3
Composition B	3.6	.10	1	NO	22.5	∞		2	1.5	2.8	2.0	10.8
	2.7	.17	1	2.8	NO		∞	1	1	9.4	1	3.4
	1.8	.10	1	2.4	8.3		∞		1	1.1	1.5	1
	.9	.03	1	1	1.3	6.0	5			3.3		
Composition C4	3.6	.18	1	NO	NO	∞		1.2	1	1	1	3
	2.7	.11	1	NO	NO		6.5	1	2.8	2.2	1	1.2
	1.8	.05	1	NO	NO			1	1	1	1	1
	.9	.03	1	NO	NO	∞	6.7	1.4	1	1	1.3	1
Black Powder	3.6	.04	NO	1.5	1	∞	∞	3.3	1.8	1.3	1.8	2.5
	2.7	.04	NO	1.3	1		2.8	1.3	1.8			2.5
	1.8	.05	NO	1.2	1	∞		1	1			2
	.9	.06	2.7	1.2	1	1	2	1	1	1	1	1.7

only the UV detector would respond to the radiation of the ethyl alcohol flame. Reading down the list of fire sources and across to observe the effect of various atmopheres in absorbing the radiation from those fire sources, one can see that the UV detector appears to be much more reliable than either the IR or the visible detectors. Conversely to this statement, attention is called to the black powder fire source. Here we see the opposite to be true. The UV detector, in almost all cases, would not sense a black powder fire, although the IR and visible detectors did respond to this flame source.

To assist in the assessment of these data, Table XVII is presented to summarize the sensor response for the seven fire sources at four distances and through seven atmophere contaminants. Column 1 displays the seven fire sources and column 2 the distances from the detector at which the tests were conducted. In this chart, the response time of the "best" detector is recorded as an absolute number in seconds. In the next three columns, the response time of this "best" detector is recorded as being equal to one and the response times of the other detectors are recorded in multiples of the response of the best detector. By way of explanation, attention is called to column 1, the M-1 propellant fire source, wherein the UV detector is scored as having a response of one and the IR detector and visible detectors as 3.6 and 3.0, respectively. This means that the IR and visible detectors did see the M-1 propellant fire. However, they took 3.6 times and 3.0 times as long to respond as did the UV. Continuing across the table, we then examined the response of only the best detector through a black powder smoke atmosphere, the signal is delayed by a factor of 1.5 times that through a clean air atmosphere. Through dust the M-1 propellant fire was not seen at all, and through water and ethyl alcohol the detector responded at nominally the same time as it did through the clean air atmosphere.

The most expeditious review of Table XVII can be obtained by reviewing the response times as a multiple of the three sensors, as shown in columns 4, 5 and 6 of the table. Here one can readily see that the UV detector responded well for all of the flame sources with the exception of the black powder. Reviewing column 5 for the response of the IR detector, one can see that the IR was incapable of seeing an ethyl alcohol and composition C-4 fire, and was only marginally responsive to the WC870, the Composition B, and the ether flame sources. The IR detector did, however, respond to the black powder flame source. The response of the visible detector is seen in column 6. This detector performed best when viewing a black powder fire, but was incapable of seeing ethyl alcohol, ether, composition C-4, and only marginally responsive to a composition B flame source.

<u>Conclusions</u> - The most important conclusion to be gained from a survey of these data is the unquestionable fact that one must carefully consider the flame source and the distance to the detector in selecting the appropriate system for use in fire detection. It would appear that the UV detector, overall, is the best for use with most of the flame sources,

and in most cases, the response time of the UV was shorter than for either the IR or the visible. There are, however, notable exceptions, probably the most prominent being that the UV detector in these tests was incapable of seeing the small black powder flame source. Other investigators* have reported that the UV detector can be used to view black powder fires, however their fire "samples" were much larger fires. For instance, MRC Corporation agrees with our tests in that they too could not see a one square foot fire at any distance. Larger fires, 0.19 m^2 and over, could be detected but only out to distances of 3.7 m. Day and Zimmerman were able to detect very large black powder fires with a UV detector.

In conducting this comparative evaluation, it was realized that the number of variables were many, and that only a relative few parameters could be addressed. These experiments, while yielding quantitative numerical results, are most valuable if used in a qualitative sense by recognizing how these tests were conducted and then relating these results to a particular plant environment and potential fire source.

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* MRC Corporation, Report No. 653, June 5, 1974, and Day and Zimmerman Corp., GOCO Contractors at Lone Star AAP, private communication.

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